G. J. Monkman, S. Hesse,
R. Steinmann, H. Schunk
Robot Grippers

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Robot Grippers

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Preface

This is the English version of the book of the same name previously published in German. However, it is not simply a translation but largely a new work as a comparison with the original will reveal. Much of the former content remains as it were but the organisation has been altered in line with Anglo-Saxon literary tradition.

Exactly at whom this book is aimed is a little difficult to summarise in a single statement. The work acknowledges the maturity of the robotics field and consequently its content is aimed largely at industrial users. Nevertheless, it will certainly also be of value to both undergraduate students in Mechatronics, mechanical and electrical engineering and post graduate researchers working in the field of robotic prehension.

References are given per chapter and, where particularly relevant, are sometimes repeated. Many refer to the original works in English, French, German and Russian, though where possible additional texts from the same author(s) are given in a second language (where available).

The Authors

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Human labour has always been associated with the acquisition of specific skills, methods, and tools making the work and its environment easier and more effective. Increasing competition from industrial robots for tasks normally carried out by human hands has led to the need for more effective handling equipment, especially prehension tools (more commonly called "grippers"). However, industrial robots are not simply a substitute for people. Their relevance is more often in applications beyond the normal ability (physical or temporal) of conventional manpower. Examples include, dirty, hazardous and repetitive work. Just as human hands are the organs of human manipulation, so are robot grippers usually the only parts in direct contact with the workpiece. For this reason they deserve special attention – to which this book is dedicated.

1.1
Grippers for Mechanization and Automation

Grippers are active links between the handling equipment and the workpiece or in a more general sense between the grasping organ (normally the gripper fingers) and the object to be acquired. Their functions depend on specific applications and include:
- Temporary maintenance of a definite position and orientation of the workpiece relative to the gripper and the handling equipment.
- Retaining of static (weight), dynamic (motion, acceleration or deceleration) or process specific forces and moments.
- Determination and change of position and orientation of the object relative to the handling equipment by means of wrist axes.
- Specific technical operations performed with, or in conjunction with, the gripper.

Grippers are not only required for use with industrial robots: they are a universal component in automation. Grippers operate with:
- Industrial robots (handling and manipulation of objects).
- Hard automation (assembling, microassembling, machining, and packaging).
- NC machines (tool change) and special purpose machines.
- Hand-guided manipulators (remote prehension, medical, aerospace, nautical).
- Workpiece turret devices in manufacturing technology.

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- Rope and chain lifting tools (load-carrying equipment).
- Service robots (prehension tools potentially similar to prosthetic hands).

In robotics technology grippers belong to the functional units having the greatest variety of designs. This is due to the fact that, although the robot is a flexible machine, the gripper performs a much more specific task. Nevertheless, these tasks are not limited to prehension alone which is why the more generic term “end-effector” is often used.

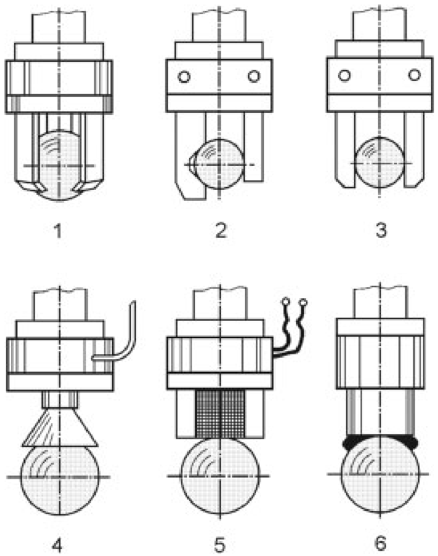
The great number of different requirements, diverse workpieces and the desire for well adapted and reliable systems will continue to stimulate further developments in future gripper design. Many experts consider the capabilities of the gripper as an essential factor for the economic effectiveness of automatic assembly systems. Experience indicates that in the future it will only be possible to respond to practical demands if flexible designs for assembly equipment are available. Consequently, grippers must become ever more flexible. Assembly relates not only to prehension and manipulation of objects but also to pressing, fitting and joining operations. Many grippers are employed for the loading of manufacturing lines, in packaging and storage as well as the handling of objects in laboratory test and inspection systems.

More recently, miniaturized grippers have been developed in order to handle delicate components in microtechnology. This has gone hand in hand with the emergence of many novel prehension methods. The number of grippers used in nonindustrial areas, e.g. in civil engineering, space research, handicraft, medical and pharaceutical engineering is steadily increasing. Hand-guided (teleoperation) or automatic manipulators are used in these areas primarily as handling machines. In addition to conventional grippers, for which the gripper jaws are shaped according to the workpiece profile, there exist numerous application specific grippers. This explains why an overwhelming proportion of corresponding patent literature is devoted to prehension concepts of unconventional design. In general, end-effectors are not normally within the delivery remit of robot manufacturers. Depending on the specific requirements, they are selected as accessories from tooling manufacturers or specially designed for the given purpose.

1.2 Definitions and Conceptual Basics

Grasping organs or tools constitute the end of the kinematic chain in the joint system of an industrial robot and facilitate interaction with the work environment. Although universal grippers with wide clamping ranges can be used for diverse object shapes, in many cases they must be adapted to the specific workpiece shape.

> **Grippers** are subsystems of handling mechanisms which provide temporary contact with the object to be grasped. They ensure the position and orientation when carrying and mating the object to the handling equipment. Prehension is achieved by force producing and form matching elements. The term “gripper” is also used in cases where no actual grasping, but rather holding of the object as e.g. in vacuum suction where the retention force can act on a point, line or surface.



1 pure enclosing without clamping
2 partial form fit combined with clamping force
3 pure force closure
4 holding with vacuum air (pneumatic force closure)
5 retention using magnetic field (force field)
6 retention using adhesive media

Fig. 1.1: Possibilities for prehension of a spherical object

Three of the most usual forms (impactive, astrictive and contigutive) of object prehension are depicted in six different examples in Figure 1.1.

One should differentiate between grasping (prehension) and holding (retention) forces. While the grasping force is applied at the initial point of prehension (during the grasping process), the holding force maintains the grip thereafter (until object release). In the many cases the retention force may be weaker than the prehension force. The grasping force is determined by the energy required for the mechanical motion leading to a static prehension force. The functional chain *drive* → *kinematics* → *holding system* is given, however, only for mechanical grippers. Astrictive vacuum suction grippers require no such kinematics [1-1].

There are some characteristic terms that are often used in prehension technology. Grippers consist mostly of several modules and components. In the following, the most essential terms used will be explained considering as an example a mechanical gripper such as the one shown in Figure 1.2.

A short glossary of further important terms used in gripper technology is briefly explained below.

Astrictive gripper: A binding force produced by a field is astrictive. This field may take the form of air movement (vacuum suction), magnetism or electrostatic charge displacement.

Basic jaw (*universal jaw*): The part of an impactive gripper subjected to movement. An integral part of the gripper mechanics, the basic jaw is not usually replaceable. However, the basic jaws may be fitted with additional fingers in accordance with specific requirements.

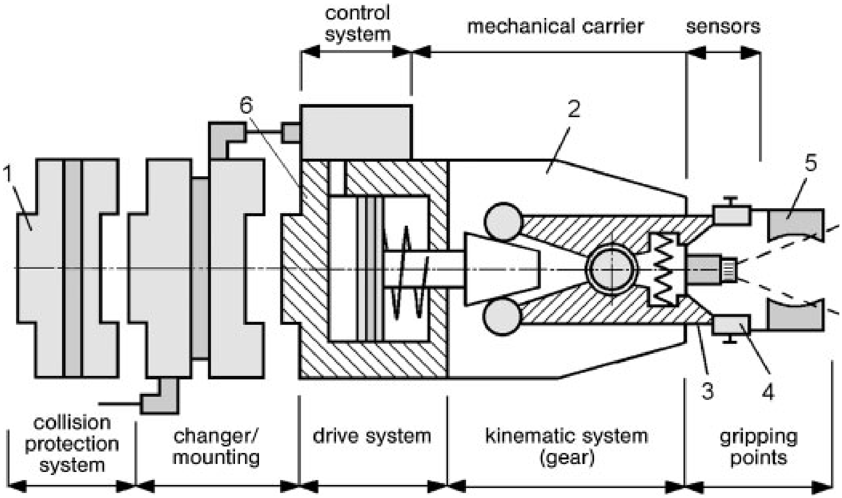
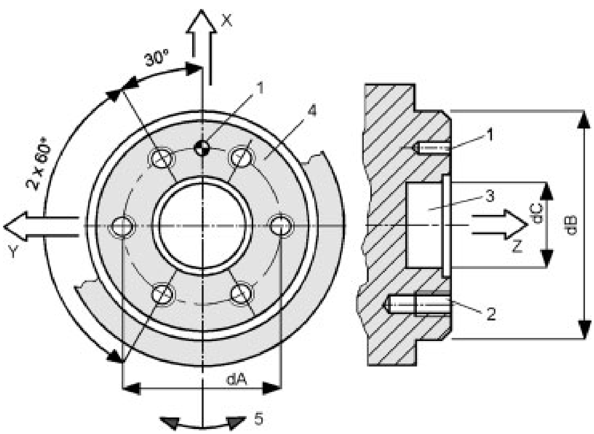


Fig. 1.2: Subsystems of a mechanical gripper
1 remote centre compliance, 2 carrier, 3 gripper finger, 4 basic jaw, 5 extended jaw, 6 flange

Basic unit: Basic module containing all gripper components which is equipped for connecting (flange, hole pattern) the gripper to the manipulator. The connecting capability implies a mechanical, power, and information interface. Figure 1.3 shows a flange design in accordance with DIN ISO 9409. This German industrial standard and its subsequent amendments contain design requirements concerning the different overall size, pitch circle diameter, centring cylinder dimensions, number of threaded holes and respective thread pitch as well as some position tolerances. The flange can also be drilled to allow feeding of power and control cables.

Chemoadhesion: Contigutive prehension force by means of chemical effects. Usually in the form of an adhesive (permatack or single use).



1 mating hole for locating pin
2 threaded securing hole
3 centring cylinder
4 flange body
5 flange rotation

dA pitch circle diameter
dB centring cylinder diameter
dC inner cylinder diameter

Fig. 1.3: Example of flange design and mounting in accordance with German standard DIN ISO 9409

Contigutive gripper: Contigutive means touching. Grippers whose surface must make direct contact with the objects surface in order to produce prehension are termed contigutive. Examples include chemical and thermal adhesion.

Control system: In most of the cases a relatively simple control component for analysing or pre-processing sensor information for regulation and/or automatic adjustment of prehension forces.

Dextrous hand: Anthropoidal artificial hand (rarely for industrial use), which is equipped with three or more jointed fingers and may be capable of sophisticated, programmed or remote controlled operations.

Double grippers: Two grippers mounted on the same substrate, intended for the temporal and functional prehension of two objects independently.

Drive system: A component assembly which transforms the applied (electrical, pneumatic, hydraulic) energy into rotary or translational motion in a given kinematic system.

Dual grippers: Two grippers mounted on the same substrate, intended for the simultaneously prehension of two objects.

Electroadhesion: Prehension force by means of an electrostatic field.

End effector (*end-of-arm tooling*): Generic term for all functional units involved in direct interaction of the robot system with the environment or with a given object. These include grippers, robot tools, inspection equipment and other parts at the end of a kinematic chain.

Extended jaw: An (optional) additional jaw situated at the end of an impactive gripper finger. It may, in preference to the finger itself, be modified to fit the profile of the object and it may be replaceable.

Gripper: The generic term for all prehension devices whether robotic or otherwise. Loosely defined in four categories: Impactive, Astrictive, Ingressive and Contigutive.

Gripper axis: A frame with its origin in the TCP (Tool Centre Point). This coordinate system is used to specify the gripper orientation. Figure 1.4 shows a gripper with three translational and three rotational degrees of freedom. The gripper frame is normally defined relative to the flange frame of the industrial robot.

Gripper changing system: A module for rapid manual, but in most cases automatic, exchange of an end-effector using a standard mechanical interface. In doing so, all power and control cables must be disconnected and reconnected.

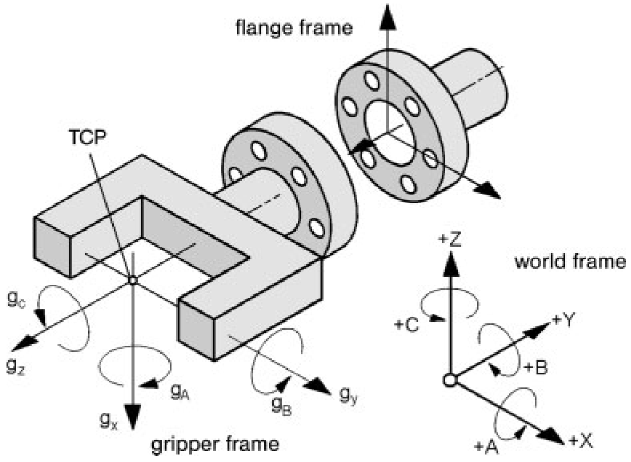


Fig. 1.4: Gripper frame

Gripper finger: Rigid, elastic, or multi-link grasping organ to enclose or clasp the object to be handled. Fingers are often equipped with extended gripper jaws at their ends. The gripper finger is usually (though not always) the active part making contact between the gripper and the object.

Gripper hand (*hand unit*): Grippers with multiple jointed fingers, each of them representing an open kinematic chain and possessing a high degree of freedom with f joints, e.g. $f = 9$.

Gripper jaw: The part of the gripper to which the fingers are normally attached. The jaw does not necessarily come into contact with the object to be gripped. Note: in some cases gripper fingers may be fitted with an additional small (extended) jaws at their ends.

Gripping area: Area of the prehension (gripper jaw) across which force is transmitted to the object surface. The larger the contact surface area of an impactive gripper, the smaller the pressure on the object surface.

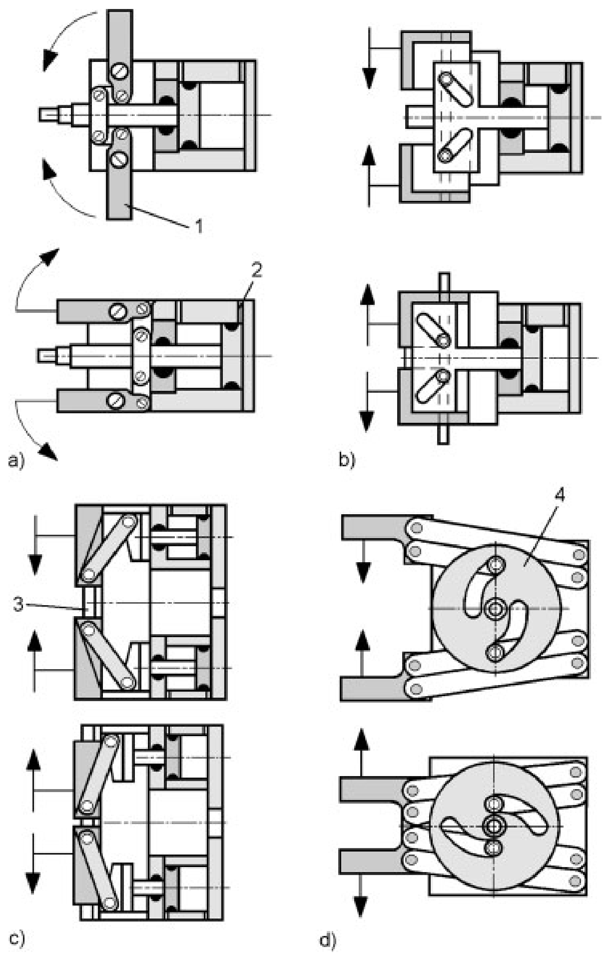
Gripping surface: The passive contact surface between object and gripper, i.e. the surface which is subjected to prehension forces.

Holding system: A term often used for an active prehension system including gripper, jaws and fingers. It may also apply to a passive temporary retaining device.

Impactive gripper: A mechanical gripper whereby prehension is achieved by impactive forces, i.e. forces which impact against the surface of the object to be acquired.

Ingressive gripper: Ingression refers to the permeation of an objects surface by the prehension means. Ingression can be intrusive (pins) or non intrusive (e.g. hook and loop).

Kinematic system: Mechanical unit (gear) converting drive motion of the prime mover into prehension action (jaw motion) with characteristic transmission rates for velocities and forces. The most often used kinematic components are lever, screw, and toggle lever gears. The gear determines the final velocity of the jaw movement, and the gripping force characteristics. Grippers without moving elements require no kinematics. Some examples of gears are shown in Figure 1.5.



1 basic jaw or finger
2 pneumatic cylinder
3 straight guideway
4 cam disk

Fig. 1.5: Pneumatically driven gripper with kinematic system for transmission of motion *(Sommer-automatic)*
a) angle gripper with toggle lever mechanics
b) parallel gripper with roller link
c) parallel gripper with two pneumatic cylinders
d) parallel gripper with cam disk

Magnetoadhesion: Prehension force by means of a magnetic field (permanent or electrically generated).

Multiple grippers: Several grippers mounted on the same substrate, intended for the simultaneously prehension of more than two objects.

Prehendability: The suitability of an object to be automatically gripped. Dependant on the surface properties, weight and strength when exposed to prehension forces. This property can sometimes be enhanced by applying such surfaces or elements (handling adapters) which are required only for a particular procedure.

Prehension: The act of acquiring an object in or onto the gripper.

Prehension planning: Deals with the problem of how to ensure stable mating between robot gripper and workpiece. A prehension strategy must be chosen in such a way that it can be accomplished in a stable manner and collision free. Post prehension misalignment of the object is undesirable. In many circumstances, special constraints must be observed in order to avoid contact with certain parts of the object (forbidden zones).

Prehension systems: Complete systems including grippers supplemented with additional units (subsystems), e.g. rotation, pivot and short-travel units, changing systems, joining (adjustment) tools, collision and overload protection mechanisms, measuring devices and other sensors.

Protection system: These are elements attached to the inner or outer part of the gripper which are activated in case of overload or collision in order to protect the robot and gripper from damage (warning signal, emergency stop activation, passive or active evasive movement).

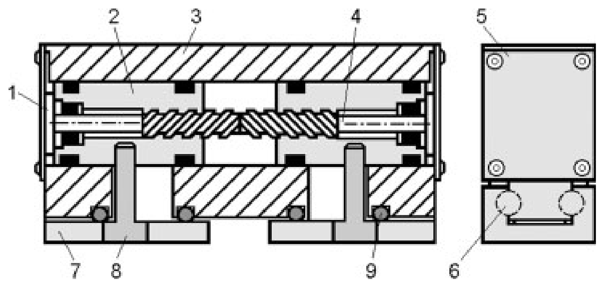
Retention: Pertains to the post prehension status of an object already held in the gripper. Note: prehension and retention forces are not always equal.

Sensor system: Sensors pertinent to the task of prehension. This may include sensors built into the end-effector, possibly with integrated data pre-processing, for position detection, registration of object approach, determination of gripping force, path and angle measurements, slippage detection etc.

Sucker: Normally refers to a passive suction element (disk, cap or cup) which does not require active vacuum suction but relies on the evacuation of air by distortion of the element against the object surface.

Suction head: A form of astrictive gripper which may consist of one or more vacuum suction elements (discs, caps or cups) freom which air is actively evacuated by means of externally generated negative pressure.

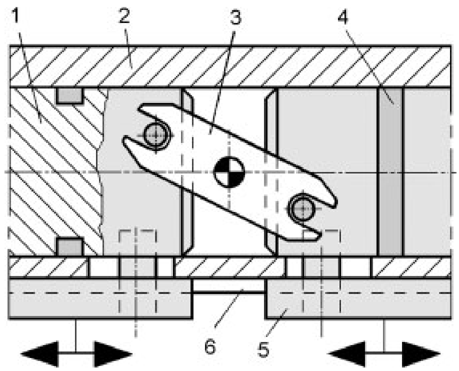
Synchronization: In the majority of 2 and 3 finger grippers it is intended that the fingers close in a uniform manner towards the centre of the gripper. In order to achieve this the motion of the fingers must be synchronized. Pneumatic cylinders, as can be seen from the example in Figure 1.6, can be moved synchronously by means of a shaft with both right and left handed threads.



1 cover plate
2 pneumatic cylinders
3 housing
4 thread shaft
5 sealing plate
6 basic jaw guides
7 basic jaws
8 securing bolts
9 seals

Fig. 1.6: Synchronization of the gripper fingers by means of a right and left hand threaded shaft

Such movement may also be realized by a gear comprising only links and levers (double swing mechanism), as shown in Figure 1.7 (see also the solution depicted later in Figure 3.15). The basic jaws are again pneumatically driven by means of cylinders integrated within the gripper housing.



1 pneumatic cylinder
2 housing or cylindrical boring
3 synchronous lever
4 sealing
5 basic jaw
6 jaw guides

Fig. 1.7: Synchronization by means of a double swing-yoke-drive (scotch-yoke drive)

TCP (*tool centre point*): Working point at the end of a kinematic chain. The TCP serves also as a programmed reference point for an end effector and as a rule determines the origin of the tool frame. A coordinate system whose origin coincides with the TCP is called *tool frame*. Multiple gripper heads may possess several TCPs (Fig. 1.8) or one main TCP with the rest being defined relative to the main TCP by tool offsets.

Thermoadhesion: Contigutive prehension force by means of thermal effects. Usually in the form of freezing or melting.

Workpiece or object: A general term which refers to the component or object to be prehended or which is already under prehension by the gripper.

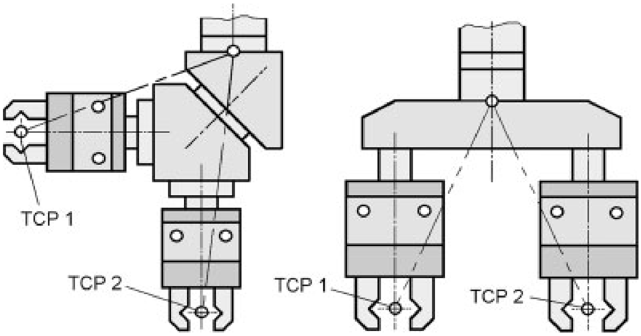


Fig. 1.8: TCPs of multiple grippers

1.3
Grasping in Natural Systems

In the course of its evolution Nature has created many different interesting grasping mechanisms. The elephant's trunk can be regarded as a biomechanical phenomenon. According to Brehm's Life of Animals, it is

"…simultaneously a smelling, feeling, and grasping organ. It is composed of ring and longitudinal muscles, according to G. Cuvier (1769–1832) these are about 40 000 separate bundles, which enable not only any twisting but also stretching and contraction".

In his work on kinematics during the second half of the 19th century, *F. Reuleaux* (1829–1905) analyzed (among others) animal mechanisms of motion [1-2]. These included the mouths of fish and bird's beaks which are also used to perform prehension tasks. The use of astrictive force though suction is also nothing new in nature. Such techniques are used by fauna as suction feet (Fig. 1.9), e.g. in cephalopods. The male of the diving beetle (*Dytiscus marginalis*) possesses stemmed suction cups on its front legs. Applying them to a surface causes spreading of the finely chitinous, semispheric caps at their delicate edges. Drawing them back then results in a reduction in pressure which in turn produces the adhesion effect. Lizards possess adhesion lamellae on their toes (dry adhesion) which enable them to traverse glass plates using their surface roughness [1-3]. There are in fact many

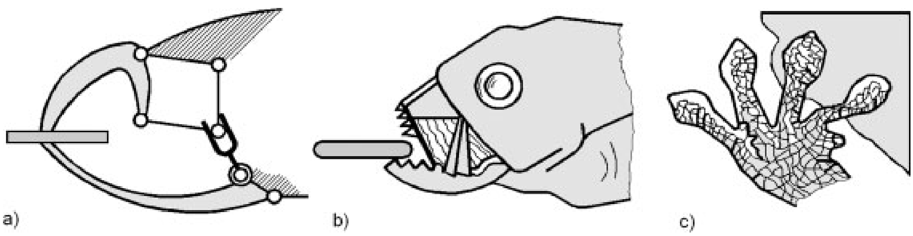


Fig. 1.9: Natural grasping, holding, and mastication mechanisms
a) bird's beak, b) fish mouth, c) suction foot

grippers whose kinematic principles are strongly related to those of Bird's beaks or ele phant's trunks, for example in paint spraying or to encompass an object (see the soft grippers in Chapters 8 and 13). In order to handle fragile objects, grippers which imitate the musculous hydrostates of squid tentacles, have been utilised. The prehension and mastication organs of insects (*Chelicerae* of spiders, *Mandibles* of biting and chewing insects like the antlions) resemble impactive grippers [1-4].

If we consider the osprey (Fig. 1.10), we can see that the problem of "grasping under complicated conditions" has been solved in the course of biological evolution in a very interesting manner. The osprey is able to grasp objects whose surfaces enjoy extremely low friction coefficients (specifically to avoid prehension by predators!) during flight.

The grasping foot exhibits long-drawn and sharp claws which make it possible to catch the prey (ingressive prehension). The lower part of the foot exhibits soft pads with a high coefficient of friction (buffered impactive prehension). During grasping these pads produce a suction (astrictive prehension) effect against the smooth surface of the object. Hence, in this case several effective prehension principles are combined. Indeed, there also exist robot grippers which prehend by impactive clamping and simultaneously use vacuum suction (Fig. 1.10b). However, none of the man made grippers possess the wealth of fine details observed in nature. Why?

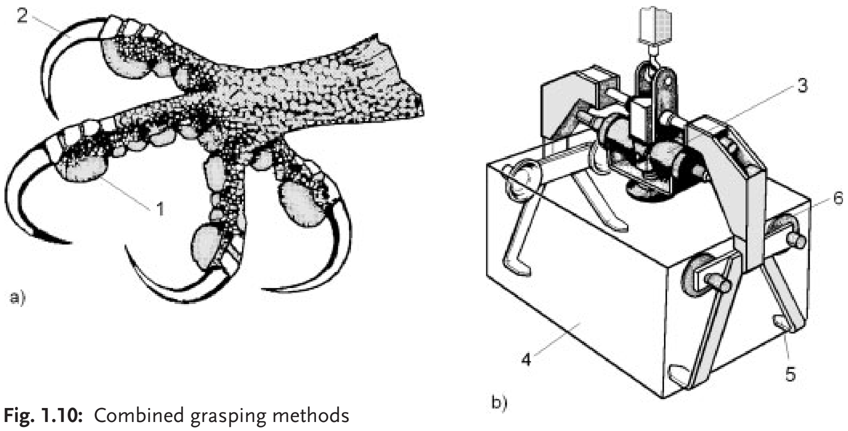


Fig. 1.10: Combined grasping methods
a) grasping foot of an osprey Pandion haliaetus, b) hook gripper combined with suction cups
1 anti slip pads, 2 claw, 3 pneumatic cylinder, 4 gripped object, 5 hook, 6 suction cup

Crab pincers are another good example often imitated by man. The crab arms end with a robust scissor mechanism which serves for both grasping and pressing. From the point of view of kinematics, it is simply a matter of the successive coupling of two four-link spherical gears (Fig. 1.11). To these ends crab arms possess the following design properties:
- They have a large pivoting angle for a small number of arm links.
- They can exert relatively large forces.
- The joints between the arm links are free from mechanical play and are capable of working under pressure over an extended range of motion.

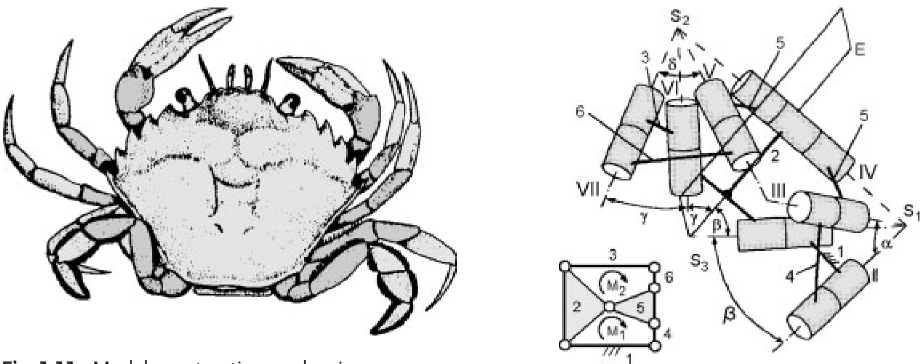


Fig. 1.11: Model construction: crab scissors
left: crab; right: kinematic scheme (four-joint chain) after [1-5];
1 frame, 2 interlink, 3 link, 4 drive swing, 5 coupler

The crab has developed an ingenious solution to the articulation between arm members. It is based on two spherical joints of polar cap form housed concentrically within one another. These spherical joints consist in turn of several additional shells whose surfaces serve as slip and contact areas. Such joints are of special interest for miniaturized mechanisms since joint solutions of the "fork head – pin" type cannot be arbitrarily downscaled.

Ball-and-socket (spherical) joints in living organisms are often coated with a jelly-like substance as a lubricant so that the connection is free from play and smooth running. In addition it may exhibit nonlinearities (stick-slip) effects.

The famous Greek philosopher Aristotele (384-322 BC) described the hands as "the tool of all tools". The 5-finger human hands represent a particularly flexible and useful grasping organ, particularly in conjunction with control though eye-hand feedback.

The bones of the hand are anatomically divided into three groups: the wrist or carpal bones (16 small bones at the root of the hand); the midhand or palm bones, and the first link (metacarpus) and finger (phalanx) bones (Fig. 1.12).

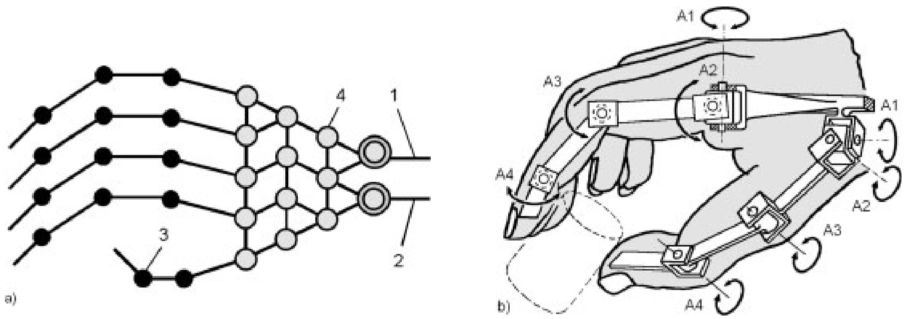
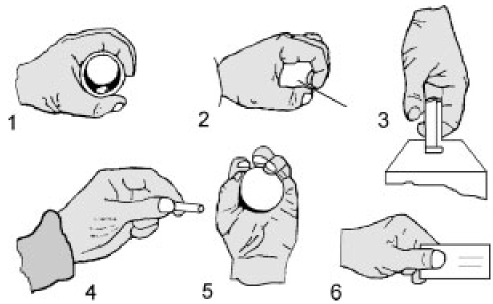


Fig. 1.12: The human hand
a) mechanical joint system [1-6], b) simplified mechanical representation.
1 radius, 2 ulna, 3 finger joint, 4 hand joint, A rotation axis

There are 8 carpal bones, 5 midhand bones (one for each finger), and 14 links (two for the thumb and three for every other finger). This anatomic constellation enables a total of 22 degrees of freedom in which as many as 48 muscles are involved.

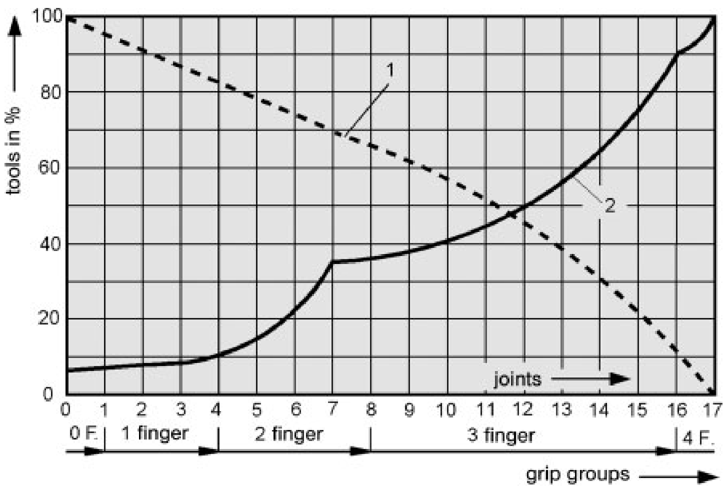
The hand and forearm muscles are involved in practicing, memorizing, retrieval, and variation in a tremendous number of separate grips. The human hand possesses ultimately 27 degrees of freedom. The exact number depends on how the muscles are classified in independent groups [1-7]. If the finely coordinated muscles are independently moved and one defines for each degree of freedom the two end and one mid positions, this alone will give 3^{27}, i.e. more than 7 billion different potential hand positions. Typical hand grips can be grouped, more or less exhaustively, into six grip classes (Fig. 1.13) [1-8 to 1-10].



1 cylindrical hollow grip
2 tip grip
3 hook grip
4 three finger grip
5 hand palm grip
6 tong grip

Fig. 1.13: The different hand grip classes

If the consideration is restricted to human activities necessary for industrial work, a direct relationship between the hand with the necessary tools and the number of fingers involved in the specific work may be observed. In other words, fingers can be replaced by tools. This relationship is illustrated in Figure 1.14.



1 number of tools
2 grip possibilities

Fig. 1.14: Fingers can be replaced by tools [1-11]

Zero fingers in the graph should be understood as movement of the arm joints only. As can be seen, the addition of the fifth finger makes negligible contribution to industrial work. About 90% of the grips involved in industrial applications can be realized with a three finger hand. Furthermore, all fingers do not possess the same strength. The middle finger is the strongest one and the little finger the weakest. The strength potential is distributed as follows: index finger 21%, middle finger 34%, ring finger 27%, and little finger 18%.

Grasping operations are always an integral part of more complicated handling strategies even in cases when they are performed automatically. Consequently, grippers should always be considered and evaluated for each individual case. As for the assembling of components, a brief procedure is shown in Figure 1.15, whereby the simple loading of a clamping device can be considered to be equivalent to the final assembly step.

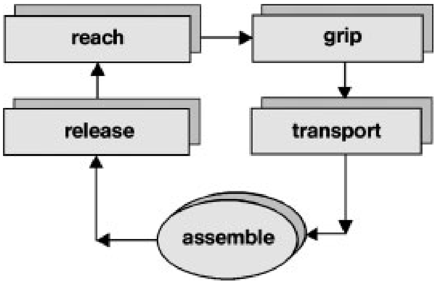


Fig. 1.15: General flow-chart of an assembly cycle [1-12]

1.4 Historical Overview of Technical Hands

The first analogies of the human hand were developed as artificial replacements: The "iron fist" of *Götz von Berlichingen* (1480–1562) possessed five separate fingers (Fig. 1.16).

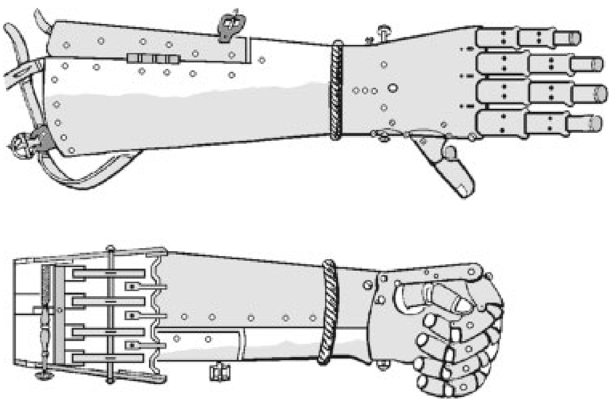


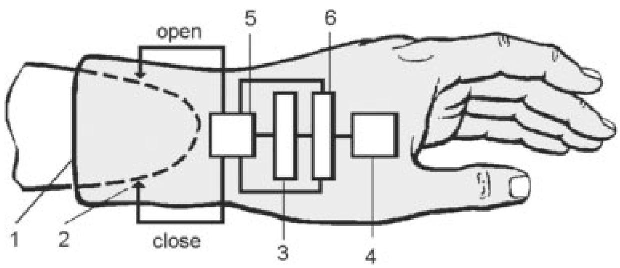
Fig. 1.16: The iron first of *Götz von Berlichingen*, knight of the Frankish Kingdom

The fingers could be passively bent, fixed and released at the push of a button. Although the hand weighs about 1.5 kg this was not considered particularly heavy for those times.

In 1564 the French physician *Ambroise Paré* (1510 – 1590) designed a mechanical hand, in which the separate fingers were equipped with individual mechanics. At that time the idea caused a sensation because it seemed to demonstrate that humans and machines operate in the same manner and there are possibly spheres where they are exchangeable [1-13].

As a result of World War I the demand for hand replacements increased. The first hand replacement driven by external energy was designed by *E. F. Sauerbruch* (1875 – 1951) and appeared in 1916. He utilized the remaining available force of the residual muscles in the amputation stump. The muscle movement was transmitted to the replacement mechanics by inserted ivory pivot pins [1-14].

The first successful use of arm stump bio-currents to control a miniaturized electromechanical system in a replacement hand was made in 1947. In the meantime such so called bio-hands are readily available and their carrying capability and functionality are comparatively good. The basic principle of operation is shown in Figure 1.17. The electromotoric *Vaduz-hand* of the Swiss *E. Wilms* (1949) had a similar construction.

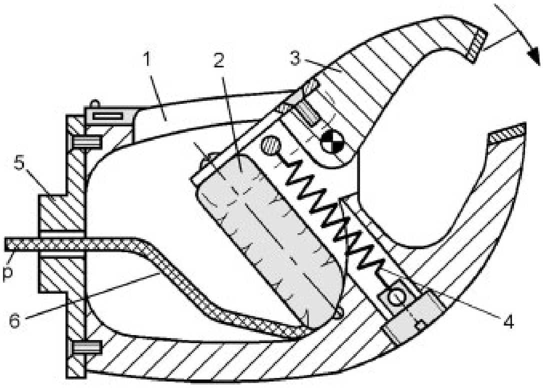


1 arm stump
2 skin electrodes
3 battery
4 gear
5 amplifier
6 motor

Fig. 1.17: Construction of a myoelectric biohand (prosthesis)

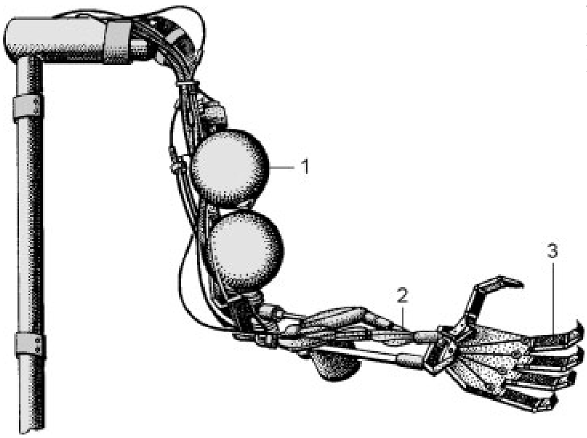
In addition to electromechanical systems, pneumatic actuation has also been used for hand replacements. Some 60 years ago an arm prosthesis driven by compressed air was developed at the orthopaedic centre in Heidelberg (Germany). The hand prosthesis depicted in Figure 1.18 is a part of it. The fluid actuator is a flexible extensible body which, when inflated, pivots the finger into a firm grip. A return spring serves to release it. Until 1965 more that 350 patients benefited from this design. The so-called *McKibben* arm exhibits similar characteristics.

In the 1950s the American *J. L. McKibben* designed a pneumatic muscle intended for prosthetic actuation (Fig. 1.19). The muscle consisted of a rubber tube with a net of inelastic threads in rhomboid pattern over, and along the length, of the surface. When pressurized the muscle inflates and simultaneously shortens. Wires transmit these length changes to the joints which in turn produce motion in the finger links. The operation of the fluid muscle as a gripper actuator is illustrated in Figure 3.15. Unfortunately, such a fluid muscle can produce only contraction forces.



1 gripper housing
2 flexible pneumatic actuator
3 wooden finger
5 fitting flange
4 return spring
6 compressed air tube
p compressed air input

Fig. 1.18: Hand prosthesis from the orthopaedic center in Heidelberg (1948)



1 rubber muscle
2 wire and wire lead
3 hand prosthesis

Fig. 1.19: Arm prosthesis with segmented rubber muscles (after *McKibben*, USA)

Another trend relates to the so-called android hands developed for special figures intended for exposition. The automats designed by *Pierre Jaquet Droz* (1721 – 1790), *Henri-Louis Jaquet Droz* (1752 – 1838) and the mechanic *Jean Frederic de Leschot* (1747 – 1824) are famous androids which caused sensations in their times [1-15]. The figures were equipped with program control (turn controller). Figure 1.20 shows the hand mechanics of one such figure.

All these, however, did not stimulate the development of robotics. Their designs contained few functioning parts and served basically to optically imitate the human hands. This said, the "flutist", a "saloon robot" for the exhibit of *J. de Vaucanson* (1709 – 1782), actually used leather holstered fingers whilst playing the flute.

The artificial hands needed today for robots and remote-controlled manipulators are substantially different. A robot hand with skilful fingers is the realization of the ancient

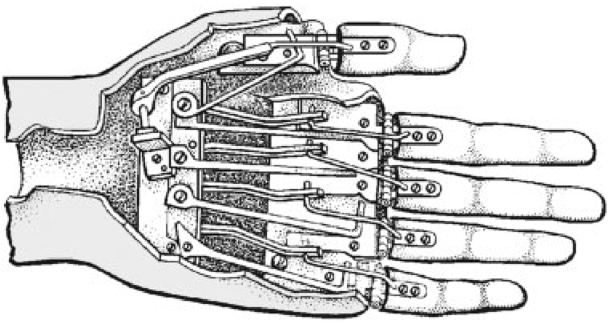


Fig. 1.20: Hand mechanics of a female "musician", an android playing harpsichord (designed by *Jaquet-Droz* [father & son] and *J.-F. Leschot*, 1774)

dream to provide machines with human abilities. The first technical hands for automation and research were developed in the 1960s. The robot hands known from such research are usually named after their institution or its place of origin, e.g., Belgrade/USC Hand, Darmstadt Hand, DLR Hand, Rhode Island Hand (for cylindrical components), Hitachi Hand, Karlsruhe Hand, Odetics Hand, Rosheim Hand, SRC Hand, Stanford/JPL Hand, Utah/ MIT Hand, and Victory-Enterprises Hand. Most of these hands are driven by electric motors. The wiring and coupling of actuator motion, mostly by means of chords, is a serious problem related to producing adequate force in the available space. A full description of dextrous hands is given in Chapter 8.

2
Automatic Prehension

2.1
Active Pair Mating

In manufacturing technology the term "active pairs" of interacting components, e.g. gripper jaw and workpiece, is often used. However, the types of the contact are also important. There are many definitions to be found in the literature. In the past the classification was limited to three gripping methods: clamping, suction, and magnetic adhesion [2-1]. Another categorization distinguishes between single-sided contact (vacuum suction, adhesion), double sided contact, and multilateral contact as in the case of shape adaptive gripper jaws [2-2]. In addition, other physical (adhesion, interaction) forces may also be considered [2-3]. The following table shows a classification (previously defined) comprising four gripping categories [2-4].

Active pair		
Gripping method	**Non-penetrating**	**Penetrating**
Impactive	Clamping jaws, chucks, collets	Pincers, pinch mechanisms
Ingressive	Brush elements, hooks, hook and loop (Velcro)	Needles, pins, hackles
Contigutive	Chemical adhesion (glues), surface tension forces	Thermal adhesion
Astrictive	Electrostatic adhesion	Magnetic grippers, vacuum suction

Impactive gripping (impact of a jaws against object surfaces) requires the motion of solid jaws in order to produce the necessary grasping force. Ingressive gripping results in surface deformation or even penetration (intrusive) of the surface down to some predefined depth (force-shape mating). Contigutive prehension implies a direct contact to facilitate gripping. Examples include chemical and thermal adhesion. Astrictive methods are based on binding forces between surfaces. Magnetic and electrostatic adhesion and vacuum suction can lift most objects even without direct initial contact.

For object retention almost all grippers operate in contact with the object surface. For initial prehension this need not always be the case. The different features concern the ac-

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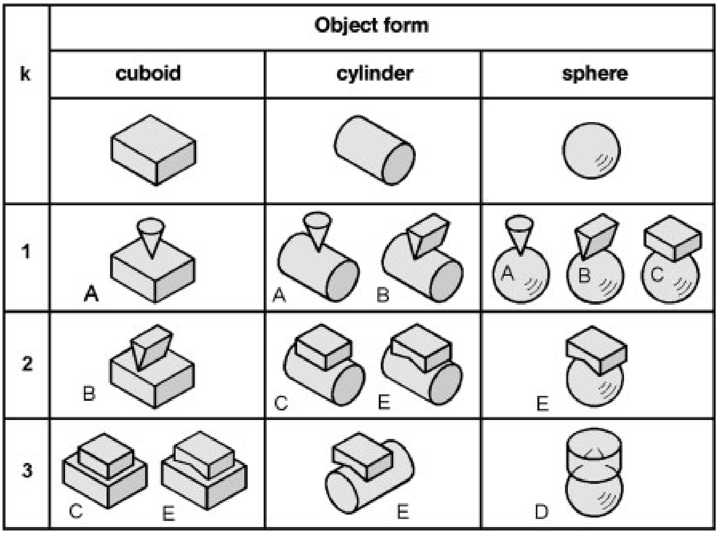


Fig. 2.1: Number of contact points between the gripped object (cuboid, cylinder and sphere) and the gripper jaw

tive gripper-object pair. Figure 2.1 illustrates possible contact methods for the three most commonly used basic geometric shapes, where *k* denotes the number of contact points. The active surfaces are designated according to the shape: A point contact, B line contact, C surface contact, D circular contact, and E double line contact. The active surfaces A to E are sufficient for the realization of a *k*-point contact; however, their positions are not always uniquely defined [2-5].

One of the most important elements of prehension is stability of grip. Misalignment of grasped components should not be possible as a result of their weight or inertia. This

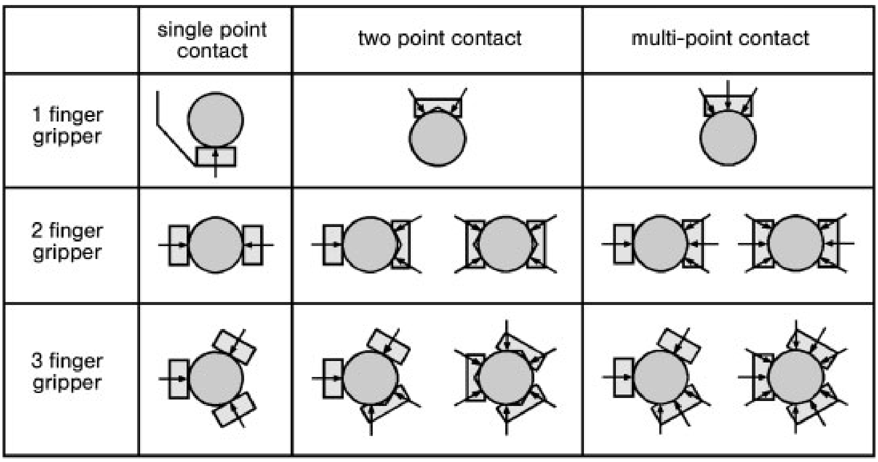


Fig. 2.2: Gripping methods depending on the number of fingers (1, 2 or 3) and contact points

should be ensured by the effective gripping force at the contact points or the active surfaces between object and gripper jaws.

Large active surfaces improve the retention stability and simultaneously allow for a reduction in gripping forces. This can also be achieved by increasing the number of active surfaces, i.e. by using more gripper jaws or more adequate gripper jaw profiles. Some examples of single, two point and multipoint contact can be seen in Figure 2.2.

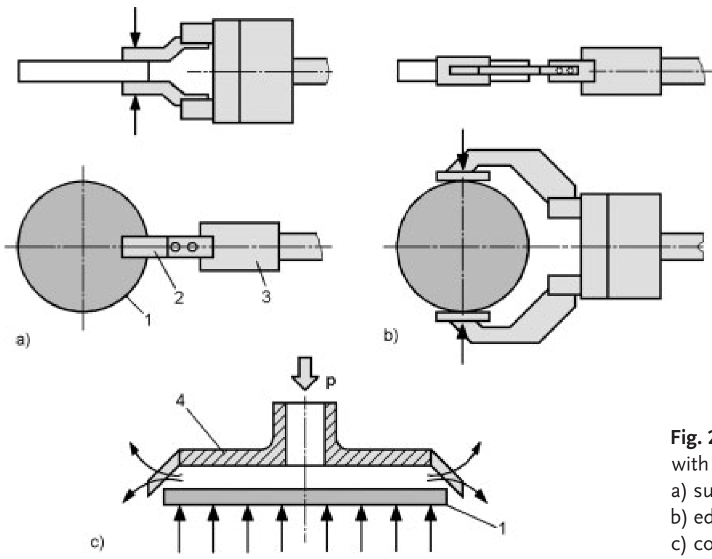
The ultimate retention stability is achieved for maximum matching of the gripper and object profiles. This can be realized by grippers with multijointed fingers as will be explained in Chapter 8. Jointed grasping organs also make it possible to compensate for irregular object shapes and to correct for position deviations. Concerning sensitive workpieces, it should be outlined that "stress free" retention is ensured by only "pure" shape matching in which the object is enclosed without any appreciable impactive forces.

A particularly sensitive surface may make the choice of another part of the object for gripping necessary. For example, contact to the upper surface of a semiconductor wafer must be avoided (Fig. 2.3 a). However, the edges or the narrow peripheral region may be used. However this does not necessarily ensure a reliable grip. Air flow grippers allow the prehension of such objects without direct contact (Fig. 2.3 c).

While such air flow grippers leave the upper surface of the object untouched, the creation of air turbulence can limit their application in clean room environments.

Similar difficulties exist in the handling of small components necessary for the assembly of microsystems. A tactile contact with the end-effector can easily lead to extensive damage to fine surface structures. For this reason, other forms of non-contact prehension, such as acoustic grippers, are of considerable interest [2-6] as illustrated in Figure 2.4.

The prime mover behind such grippers is a piezoelectric oscillator, normally operating at frequencies above 20 kHz. AC voltages applied to the piezoelectric disk causes mechanical distortion in an oscillatory manner which leads to the generation of acoustic (standing) waves. The acoustic wave pressure compensates gravitational forces on the object (air



1 workpiece
2 gripper jaw
3 parallel gripper
4 air flow gripper

p compressed air

Fig. 2.3: Gripping of a disk with sensitive upper surface
a) surface prehension
b) edge contact
c) contactless holding

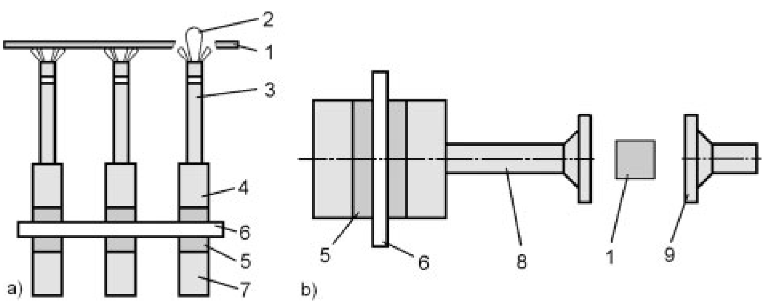
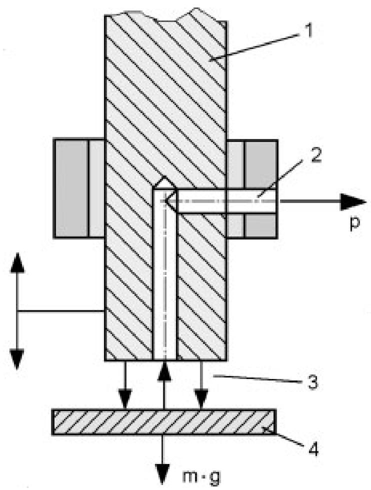


Fig. 2.4: Air cushion holding of small parts using acoustic waves
a) acoustic principle, b) acoustic gripper, 1 hovering component part, 2 sonic profile, 3 horn, 4 front oscillator, 5 piezo-ceramics, 6 node plate, 7 back oscillator, 8 front part with mechanical impedance converter, 9 reflector

cushion effect). The first devices of this type were designated as minimum-tactile because, when grasping for example a wafer, an additional lateral attachment point is necessary in order to define the position of the component in the x-y plane. These attachment points are necessary for object manipulation even though the retention forces result from acoustic waves. Such systems have no effect on the laminar irrotational flow needed in clean rooms [2-7] to [2-9].

Another version of contactless gripper is shown in Figure 2.5. The object is lifted by vacuum and simultaneously pushed away by a powerful acoustic wave. This creates a gap between the hollow sonotrode and the workpiece resulting in contactless prehension [2-10]. This technique makes possible the transport and manipulation of chips in the semiconductor industry.

As already shown in Figure 2.2 single finger grippers with only one point contact do exist. Such grippers resemble a hook and can be compared with a bent finger. They find application mainly in lifting tools and hand guided manipulators and to a lesser extent in au-



1 sonotrode
2 vacuum connection
3 slit
4 component part

p vacuum
m object mass
g acceleration due to gravity

Fig. 2.5: Contactless gripper

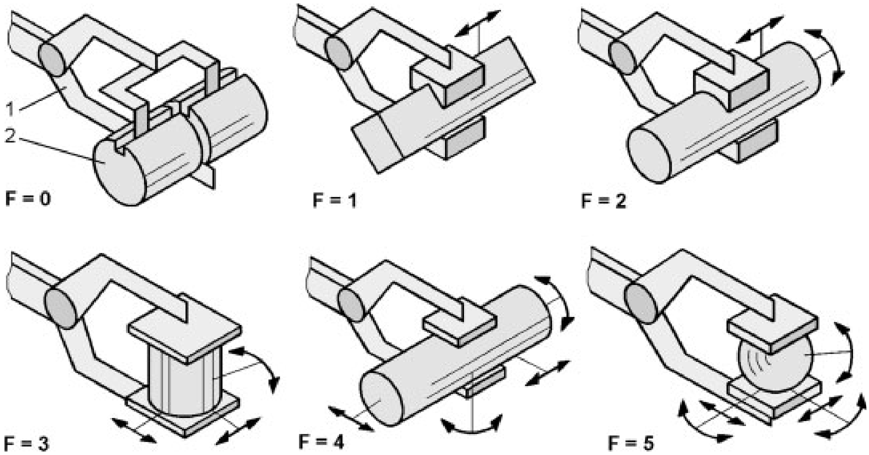


Fig. 2.6: Different active pairs with degree of freedom $F=0$ to $F=5$
1 gripper jaw, 2 workpiece

tomated handling and manufacturing technology because the position of the component in the "gripper" is only approximately defined.

Figure 2.6 shows typical situations of two point prehension and the corresponding remaining degrees of freedom.

In each case the degree of freedom F indicates the rotational and translational axes which are not secured by the matching of forces. When the forces acting upon an object during handling exceeds the frictional forces at the gripper jaws, the workpieces can become misaligned only in directions defined by these axes. At the same time, it should be kept in mind that the clamping forces cannot be arbitrarily increased. When the object is held by force matching and the pressure on the corresponding contact points is too high, surface damage to both object and gripper jaws may occur. The upper limit for prehension force is dictated by the allowable surface pressure, depending in turn on the contact force and the coefficients of elasticity of the gripper jaw and object materials. The following relationship is valid for point and line shaped contacts:

$$p = 0{,}418 \sqrt{\frac{F_K \cdot E_r}{L}\left(\frac{2}{d} \pm \frac{1}{r}\right)} \quad \text{in N/mm}^2 \tag{2.1}$$

F_K contact force [N]
E_r average coefficient of elasticity [N/mm^2]
d diameter of the gripped object [mm]
$\pm$ (+ convex gripper jaw shape; − concave gripper jaw shape)
r radius of curvature of the gripper jaw [mm] ($r=\infty$ corresponds to plane surfaces)
0.418 empirical constant
L contact line length [mm]

The average elasticity coefficient E_r may be derived from the different gripper jaw and workpiece materials (2.2):

$$E_r = \frac{2 \cdot E_t \cdot E_s}{E_t + E_s} \tag{2.2}$$

E_t Young's modulus of object
E_s Young's modulus of gripper jaw

Corresponding computational formulae for some typical contact situations are summarized in Figure 2.7.

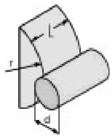
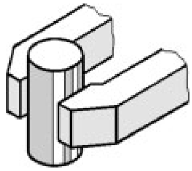
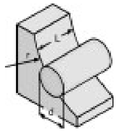
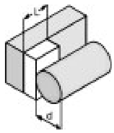
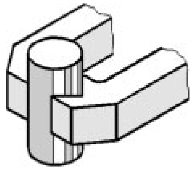
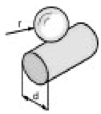
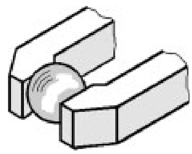
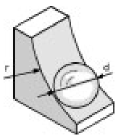
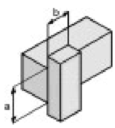
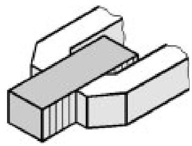
	contact	**surface pressure *p***	**gripper jaw shape**
line contact		$p = 0{,}418 \sqrt{\frac{F_K \cdot E_r}{L}\left(\frac{2}{d}+\frac{1}{r}\right)}$	
		$p = 0{,}418 \sqrt{\frac{F_K \cdot E_r}{L}\left(\frac{2}{d}-\frac{1}{r}\right)}$	
		$p = 0{,}418 \sqrt{\frac{2 \cdot F_K \cdot E_r}{L \cdot d}}$	
point contact		$p = \mathrm{m} \cdot \sqrt[3]{\frac{F_K \cdot E_r^2}{r^2}}$	
		$\frac{d}{2} < r$	
surface contact		$p = \frac{F_K}{a \cdot b}$	

Fig. 2.7: Two surface contact (jaw-object).

The coefficient m appearing in the case of point contacts can be obtained as a function of the parameter $(2 \cdot r)/d$ from the following table:

$(2 \cdot r)/d$	m	$(2 \cdot r)/d$	m
1.0	0.388	0.40	0.536
0.9	0.400	0.30	0.600
0.8	0.420	0.20	0.716
0.7	0.440	0.15	0.800
0.6	0.468	0.10	0.970
0.5	0.490	0.05	1.980

The contact force F_k differs from the gripping force F_G. Thus, for example in the case of prismatic jaws, the contact force is decomposed into two. In principle, low surface pressure causes little abrasion which is important for the employment of grippers in clean room applications.

Example: A cylindrical component part of length $L = 30$ mm is held in a prism, as depicted in Figure 2.8. Both contact pieces are made from steel. What is the maximum Hertzian pressure between the object and gripper jaw?

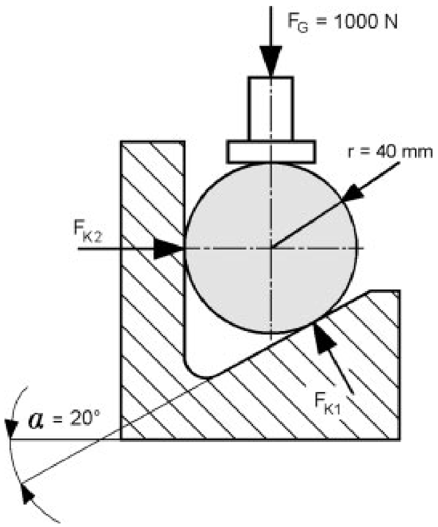


Fig. 2.8: Example of simple impactive prehension

$$F_{K1} = \frac{F_G}{\cos\alpha} = \frac{1000\ \text{N}}{0.94} = 1060\ \text{N}$$

$$F_{K2} = F_{K1} \cdot \sin\alpha = 1060 \cdot 0.342 = 362.5\ \text{N}$$

$$p_{max} = 0.418 \cdot \sqrt{\frac{F_{K1} \cdot E}{r \cdot L}} = 0.418 \cdot \sqrt{\frac{1060\ \text{N} \cdot 2{,}1 \cdot 10^5\ \text{N/mm}^2}{40\ \text{mm} \cdot 30\ \text{mm}}} = 180\ \frac{\text{N}}{\text{mm}^2}$$

The coefficient of elasticity in N/mm^2 is given at 20 °C by:

Steel	2.10×10^5	**Brass**	0.90×10^5
AlCuMg	0.72×10^5	**PVC**	0.03×10^5
GG 30	1.20×10^5	**G**	0.80×10^5

For example, the case-hardened material C10 has a Herzian pressure $p_{zuin} = 1470$ N/mm^2. Deformation of the contacting parts also occurs at the contact points. Figure 2.9 shows two such examples.

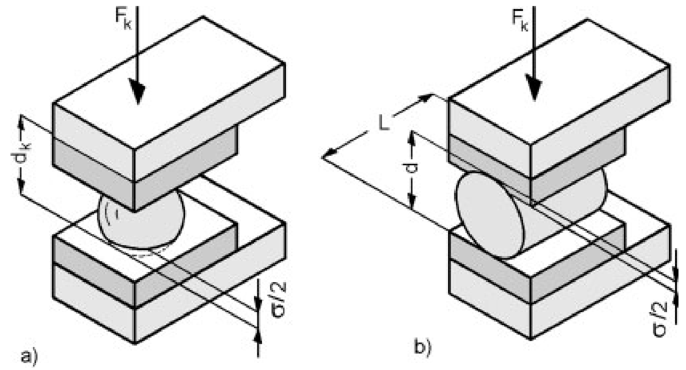


Fig. 2.9: Contact deformation of gripper jaws
a) sphere-plate, b) cylinder-plate

The total flattening σ of the two gripper jaws, can be obtained in the case of sphere-plate or sphere-sphere contacts by the following equation:

$$\sigma = 1.23 \sqrt[3]{\frac{F_k^2}{E^2 \cdot r}} \tag{2.3}$$

E Young's modulus [N/mm^2]
F_k pressure force, contact force [N]
r radius of curvature of the sphere, $r = \frac{d_K}{2}$ [mm] (2.4)

For different Young's moduli $E = \frac{2 \cdot E_1 \cdot E_2}{E_1 + E_2}$ (2.5)

Similarly, if both parts are curved, the radius of curvature is obtained as a harmonic mean

$$\frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_2} \tag{2.6}$$

The flattening of the pair cylinder-plate cannot be computed by the Hertzian equations.

Instead of reducing the prehension force by a reduction in surface pressure, the augmentation through ingressive techniques can serve to accomplish the same. Fine points penetrating the workpiece surface, produces a kind of "mini-shape matching". Initially, the points are pressed into the object to a penetration depth not exceeding 500 μm which allows a reduction in the necessary gripping force. There are two possibilities in realizing this:

- Mini-shape matching utilizing available roughness: the matching makes use of the smallest available unevenness objects surface: a kind of mini range form matching.
- Mini-shape pairing creating roughness: a microstructure is created by applying force. The active points protrude by no more than 600 μm from the jaws. A diamond needle with an angle of 130° penetrates about 0.2 mm of steel for an applied force of 100 N.

The general parameters and characteristics specifying the active matching in the gripping process can be summarized as follows:

- Spatial orientation of the gripper relative to the handling equipment.
- Resulting force, which depends on the mass and inertia, and includes centrifugal force.
- Geometry of the object and its surfaces, position of the centre of gravity (mass moment of inertia).
- Design of the gripper jaws in connection with the distribution of forces, including shape and force matching.
- Surface properties of the workpiece and the gripper jaws, rigidity, impact sensitivity.
- Environmental effects, e.g. dust and other contaminants, temperature and vibration.

2.2 Strategy and Procedures

2.2.1 Prehension Strategy

A gripping strategy must include the complete prehension plan, taking into account all possible uncertainties relevant to the process involved. Consequently, the main purpose of the strategy is the programmed or autonomous implementation of prehension. The properties of the location chosen for gripping are of essential importance. This can be characterized as follows:

- Fixed gripping point, e.g. prehension from a magazine or stack.
- Migratory gripping point, e.g. prehension from a running conveyor belt.
- Oscillating gripping point, e.g. prehension of a part rolling back and forth.
- Unknown gripping point which must be determined by sensory perception, e.g. "acquire from table top", including possible re-prehension of parts that have slipped.
- Unknown three dimensional gripping point, e.g. "take out from the box".

The accessibility of the location chosen for prehension is also important. The motion of the gripper towards and away from this location should be possible without danger of collision both when the gripper is empty or occupied. The required free space is referred to as a handling or access channel. Incidentally, the choice of robot plays a large role here. A six axis manipulator is required to position a gripper in all possible positions and orientations in the given 3 D work envelope.

The strategy for gripping a given workpiece can be:
- Predetermined; The operations required to achieve a reliable grip at the corresponding contact points are pre-programmed.
- Variable; operations are only briefly defined and can be adaptively matched to the situation in accordance with the information supplied by sensors.

Adaptive grippers possess either integrated or external monitoring sensors which implies the need for specific data processing techniques. Integrated sensors can be used to measure the stability of the object held and prompt re-acquisition of parts that have slipped. Force sensors provide signals for control of prehension force, for example in order to avoid deformation of thin-walled objects. Sensors can also monitor the handling of interlinked or double components.

The application of robot vision can help ensure more flexible prehension strategies. This allows the generation and realization of a corresponding sequence of operations for each individual prehension step in order to achieve a stable grip. For example, to identify the nature and position of workpieces within the workspace, to determine accessibility and collision avoidance.

The necessary methods of image processing for identification purposes (filtering, threshholding, edge detection and enhancement, segmentation, adjacent structure examination, invariant criteria computation, object position, determination, classification etc.) will not be dealt with in this book. For further details the reader should refer to one the many available texts on the subject.

Difficulties in a gripping task depend basically on the state (location and orientation) of the corresponding objects. The objects may be available in the following different states:
- The workpiece is positioned and oriented. The parameters X_w, Y_w, Z_w, α_w, β_w, and γ_w, defining the six spatial positions are known. In this case it should be noted that in some cases certain object surfaces must be avoided as gripping zones, e.g. the collet zone (Fig. 2.10). This is the zone used to secure the position of a component later and should not be damaged during the prehension process.

> The following zones must be determined for an object to be handled: forbiden zones, reserved zones, prehension zones, and support zones. The necessary safety margins must be observed in each case.

It is essential that:
- Reserved (already held) and prehension zones do not overlap.
- Prehension zones are located as closely as possible to the objects centre of gravity.
- The minimum active gripper jaw width amounts to at least 5 mm.
- Double jaw grippers, counteracting large gyration radii, are used for workpieces longer than 200 mm.

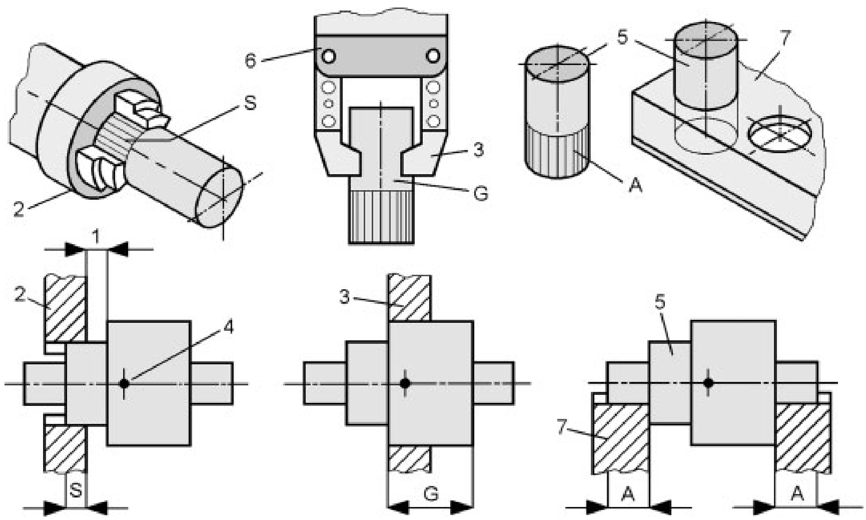


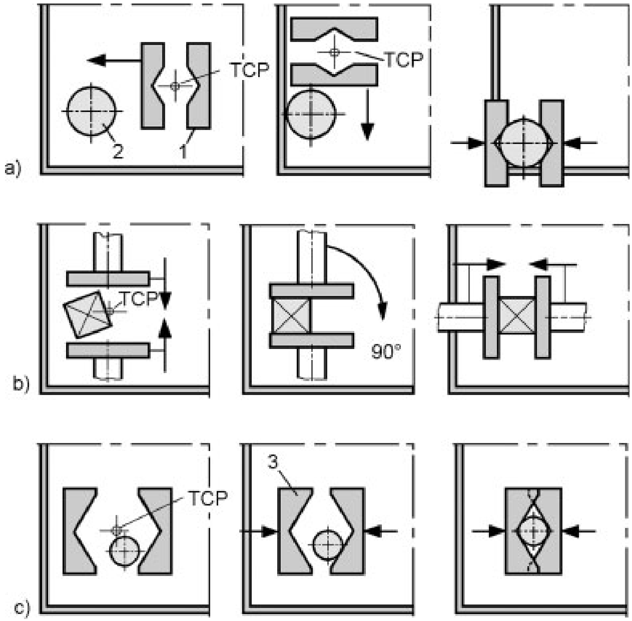
Fig. 2.10: Handling zones of a workpiece
1 safety margin in front of the clamping tool, 2 chuck, 3 gripper jaw,
4 centre of gravity, 5 workpiece, 6 gripper, 7 magazine,
A support zone, *G* prehension (grip) zone, *S* reserved zone

The above zones may experience geometrical changes in the process of machining and may need to be redefined during prehension planning. The access method for the gripper is often determined by the position of a component part in a workpiece holder or magazine.

The most important practical cases are discussed below:

- **A workpiece is lying on a plane surface with indeterminate position.** The uncertainties in the workpiece position my be eliminated without extensive sensory hardware simply by pushing against predetermined constraints prior to the act of prehension (Fig. 2.11). Such preparatory operations are slow but positioning may be accelerated with the help of vibratory feed systems or by using appropriately formed gripper jaws.
  Grippers with integrated sensors permit a more focused handling of the object as illustrated in the example of Figure 2.12. The extent of the procedure that has to be performed depends on predetermined parameters.

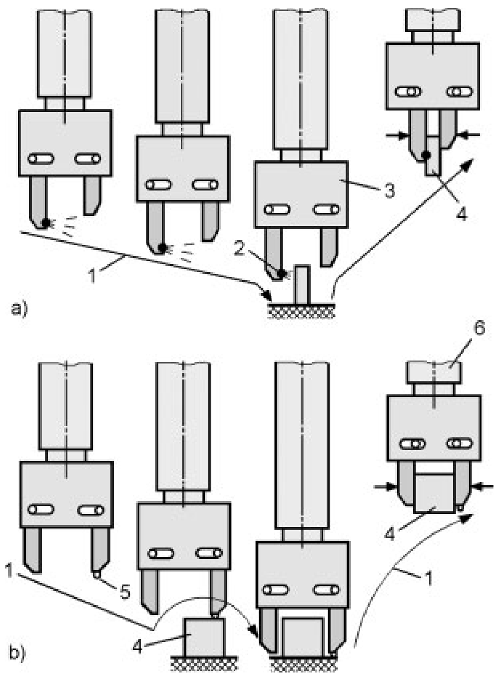
- **Several workpieces are lying on a plane surface with indeterminate positions.** The components are randomly scattered and possibly overlap (see Fig. 2.13 a). Objects located must then be analyzed to determine their accessibility. The prehension points must be accessible and reachable within the available approach space. This may require optical sensors and algorithms which generate a search path and guide the gripper towards the next prehendable object.
  The gripping sequence can be also determined by computer. An algorithm attaches a table to each workpiece, in which all access conditions are set. The optimum prehension sequence is derived from a multidimensional access matrix generated from the



1 gripper jaw
2 object
3 prismatic jaw

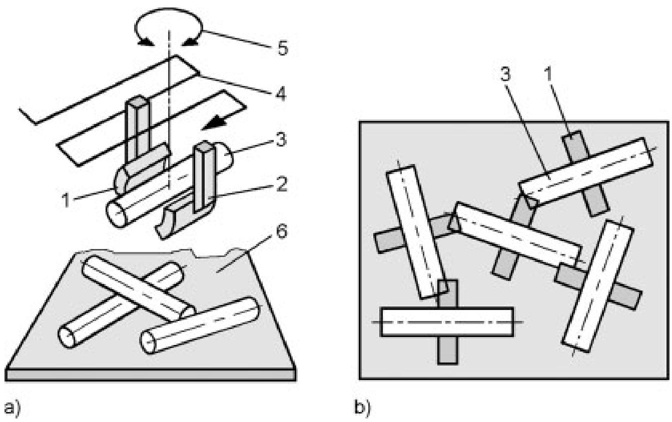
TCP Tool Centre Point

Fig. 2.11: Precise object position Maintenance
a) pushing with the outer jaw side
b) pushing with the inner jaw side
c) centration with a prismatic jaw



1 motion path
2 ultrasonic detector
3 gripper
4 workpiece
5 tactile sensor
6 handling equipment

Fig. 2.12: Sensor guided prehension
a) with contactless sensor
b) with contact sensor



1 gripper jaw
2 gripper finger
3 workpiece
4 search path of the gripper
5 rotation axis of the gripper
6 table surface

Fig. 2.13: Gripping of components distributed over a surface
a) grip settings, b) detection field

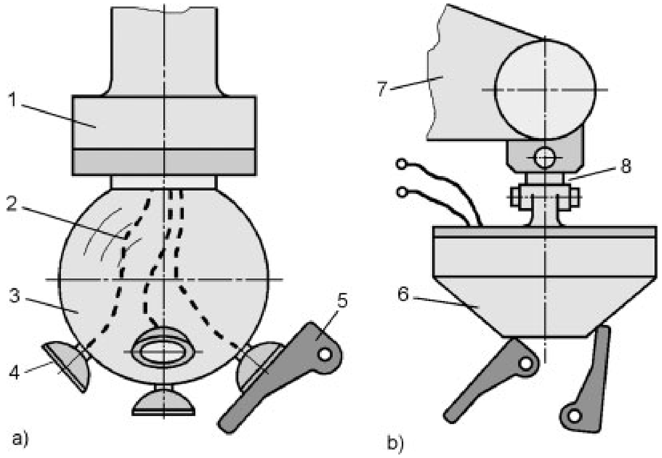
collection of access tables. Initially, columns containing solely accessible elements are determined. Once such a column is identified the gripping of the workpiece may commence. Afterwards the column is deleted and the procedure is repeated until all accessible components have been removed [2-11].

- **Several disordered workpieces in a volume.** This situation is often referred to as "random bin picking". All object location and orientation parameters are unknown. Selectively removing one (and only one) part is difficult and normally requires the use of several sensor types. The search for a prehendable object can proceed through searching motions of the manipulator itself, though more elegant is an analysis of the optically recorded scene. In reality vibratory feeders are a far better solution. By this method the parts are separated and correctly orientated prior to gripping. The problem of selectively removing different parts (such as nuts and bolts) mixed in a bin is really a "non-problem". Such components should simply not be mixed together in the first place!

Combined isolation and orientation is a technically realizable procedure incurring reasonable costs. The random gripping from the box requires special, usually astrictive, grippers. Figure 2.14 shows two examples. In Figure 2.14 a a ball-shaped bellows is dipped into the bin and then inflated in order to achieve contact between at least one integrated vacuum suction cup and an object. The manipulator then moves it to another machine for orientation.

In the case of ferromagnetic objects, the procedure shown in Figure 2.14 b using a magnetic gripper is similar. However, the danger of prehending a plurality of objects is much greater.

Another suitable prehension principle (see Fig. 2.15) uses several magnets, arranged in a matrix. Parts picked up from a bin adhere to one or more magnets. Binary sensors positioned on each magnet surface indicate which magnets are occupied. The orientation of components with well pronounced longitudinal axes can be recognized from the charac-



1 gripper base, flange
2 vacuum lead
3 inflatable balloon
4 vacuum suction cup
5 workpiece
6 electromagnetic gripper
7 robot arm
8 double joint

Fig. 2.14: Random gripping from a box
a) system using vacuum suction (German Patent B 56 G 47/90)
b) electromagnetic gripper

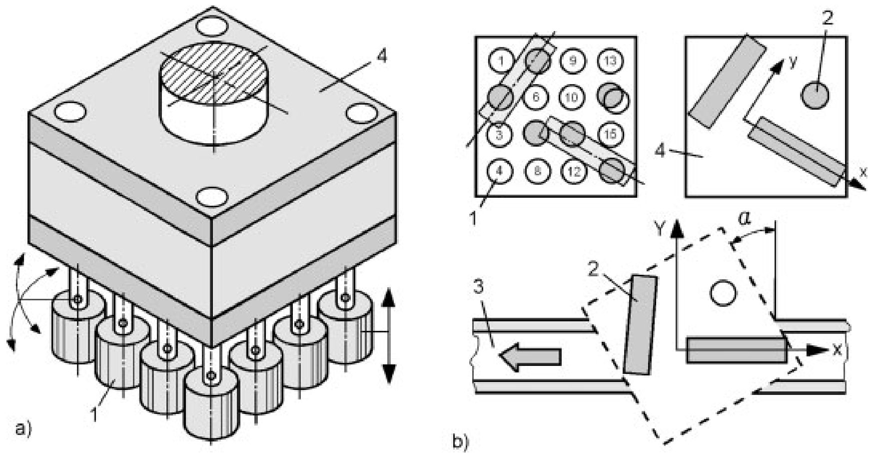


Fig. 2.15: Magnetic gripper with active area consisting of separate magnets having variable vertical position and angle
a) general view of the gripper, b) orientation determination of gripped parts
1 magnet, 2 workpiece, 3 conveyor, 4 gripper housing

teristic occupation pattern [2-12]. Finally, the acquired components may be selectively deposited in the correct order at an appropriate destination (e.g. conveyor belt). This requires that each magnet be controlled independently. The main drawback of this design results from the relatively large number of single moving components and its correspondingly large mass.

There are also magnetic grippers which form part of an "intelligent" separator system whereby the post prehension magnetic field strength can be reduced according to information received from a mass sensor. This helps eliminate the retention of an excessive number of objects. The remaining object, the orientation of which may remain unknown, is correctly orientated in a further process.

- **Simultaneous prehension of several parts.** The workpieces are ordered in rows and columns and must be grasped together, e.g. from a pallet or magazine. Additional problems may occur if the number or size of the parts changes. In such cases a certain degree of computer workpiece management is necessary. Depending on the situation, one can choose column by column, row by row or random gripping. However, the storage pattern should remain unambiguously describable after acquisition. The extraction sequence is then determined by computer.
  The orientation of the workpieces is important in the so-called multiple or package grips because the object tolerances may result in indeterminate consequences. The dimension tolerances have no effect in the example depicted in Figure 2.16 a but for the case shown in Figure 2.16 b they can result in slippage. One corrective measure is to introduce a degree of mechanical compliance such as a pivoted jaw (Fig. 2.16 c). The deliberately shape formed prehension shown in Figure 2.16 d encloses the object in all axial directions but unfortunately in the majority of cases its technological realization is unfeasible.

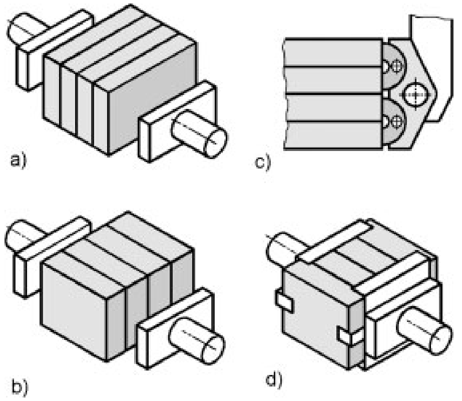


Fig. 2.16: Gripping of objects in a package
a) gripping the stack longitudinally
b) gripping the stack transversally
c) gripping with a pivoted jaw
d) completely shape formed grip

- **A workpiece is to be gripped for joining.** The assembling of electronic components is an example of the necessity to consider specific technological requirements when choosing an appropriate prehension method in order to ensure trouble free mounting. Components with wires must be grasped in such a way that lead alignment is possible (Fig. 2.17). This is a practical example of the classical "peg in hole" problem. Appropriately selected gripping points, leaving only a short protrusion of wire, help to increase assembly speeds. The points at which the wires are grasped are important. Too short a protrusion results in the need for additional hardware to complete full insertion following the gripping operation. Too long a protrusion may result in lead bending and consequent insertion failure [2-13]. Gripper access also requires some free space for mounting *b* (Fig. 2.17 a) which is given by:

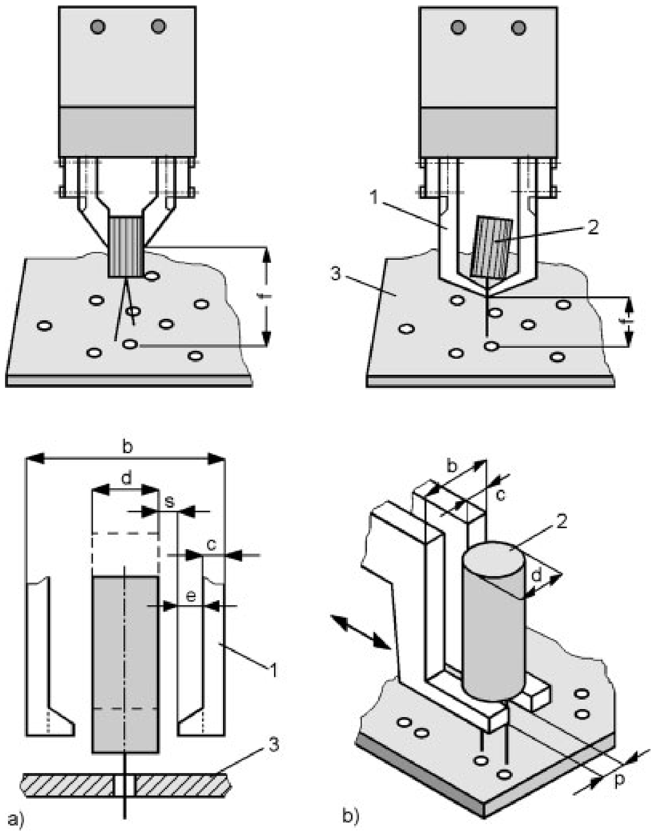
$$b = d + 2 \cdot (s + e + c) \qquad (2.7)$$

The necessary free mounting space is smaller when the component remains free, i.e. the fingers are offset (Fig. 2.17 b). In this case

$$b = p + 2 \cdot (c + s) \qquad (2.8)$$

holds because the gripper acts laterally.

where:
d diameter of the component
c finger width
p lead wire diameter
e prism depth
s free space



1 gripper jaw
2 object
3 printed circuit board

f separation join patch (opening) – gripper jaw
s free space

Fig. 2.17: Example of appropriate choice of gripping point
a) gripping at the component body, b) gripping at the lead wires

It is little wonder that the electronics industry has now largely gone over to surface mount technology – an excellent example of the "design for assembly" philosophy.

- **A workpiece is delivered on a moving conveyor.** The direction of movement is known. This case requires a specific form of prehension strategy. The manipulator must be set in motion and the prehension takes place within the synchronous range of movement of both gripper and object. For such operations it is necessary to use robots with structurally variable control algorithms ensuring optimum timing and free from overshoot. Most modern robots have such capabilities and algorithms applicable to older generations of PLC controlled automation will not be discussed here.

In summary: the choice of automated gripping strategy requires decision making at three levels:
- Strategic decisions, i.e. the gripping strategy for a predefined object in a given environment.
- Coordination decisions, i.e. the selection and application of the strategy which is most feasible for settlement of the corresponding prehension task.
- Executive decisions, i.e. the acquisition of information, the formulation of parameters, the assurance of access, etc.

Example of a prehension strategy

Sheet metal plates stored in shelves are to be removed using a vacuum suction head attached to a hand guided manipulator. The shelf depth and the weight of the plates make access difficult. The strategy is illustrated in Figure 2.18:

I. With the tray (3) pulled out, the vacuum crossbar (1) is inserted over the stack of plates.
II. The first plate is slid out and tilted onto the tray.
III. Suction is released and the vacuum crossbar placed over the entire plate surface.
IV. With renewed vacuum suction the plate is lifted from the stack.

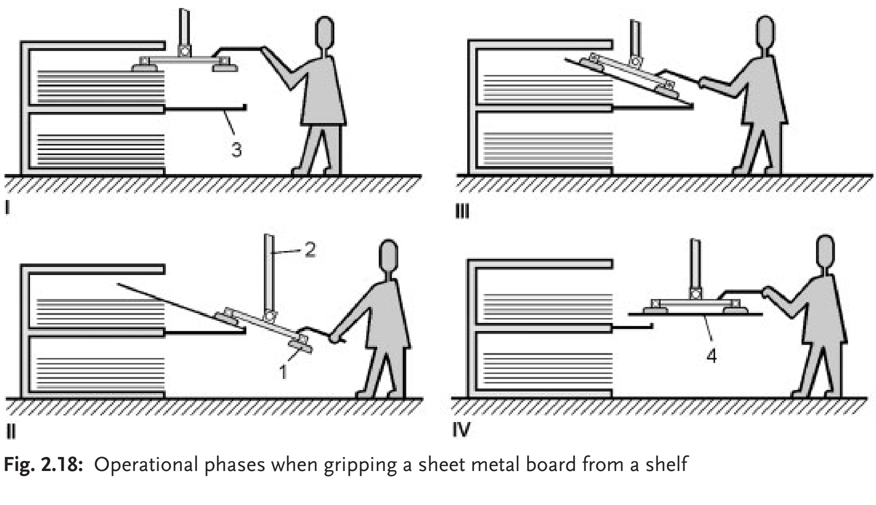


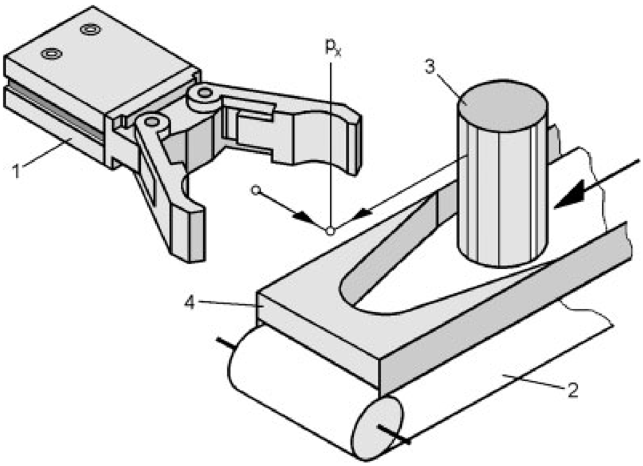
Fig. 2.18: Operational phases when gripping a sheet metal board from a shelf

2.2.2 Gripping Procedure, Conditions and Force

Gripping denotes the fundamental motion consisting of object prehension and retention.

The gripping procedure can be divided into four phases:

- Preparation for contact, e.g. by appropriate orientation of objects following a predefined motional pattern. The example illustrated in Figure 2.19 shows the use of constraints to force an object into a predefined position (p_x) using the motion of a conveyor belt.
- Prehension by establishing contact between object and gripping surfaces. At this stage the workpiece is subjected to static forces and moments.
- Retention of the object during its manipulation in space or, in some cases, moving, rotating, or even (in rare cases) mounting. Dynamic forces and moments occur in the course of motion or task related procedures.
- Release of the object at its destination, e.g. by switching-off the vacuum supply and possibly using the assistance of an integrated ejection mechanism.



1 gripper
2 conveyer
3 workpiece
4 centring tool or prism

p_x gripping position

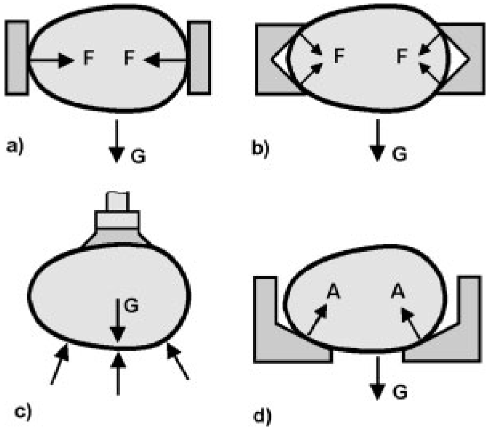
Fig. 2.19: Use of a mechanical constraint for object positioning

How does a man grasp a component with unusual shape and sensitivity to pressure?

When gripping an egg, it is first slightly raised and then enclosed by the finger tips. The fingers surround the egg from the bottom to the top, i.e. shape conformation. Thus the egg is firmly captured without the application of undue force. To achieve the same with rigid robot grippers another strategy is required.

In principle, the following methods can be used to grasp and hold an object:

- Impactive: spanning between clamps or jaws (which may be augmented with compliance or object capture).
- Astrictive: attractive forces such as vacuum suction, magnetic field, electoadhesion.
- Ingressive: hackles, needles (may also be intrusive) etc. Not of course suitable for the prehension of eggs!



A pressing force
F clamping force
G gravitational force

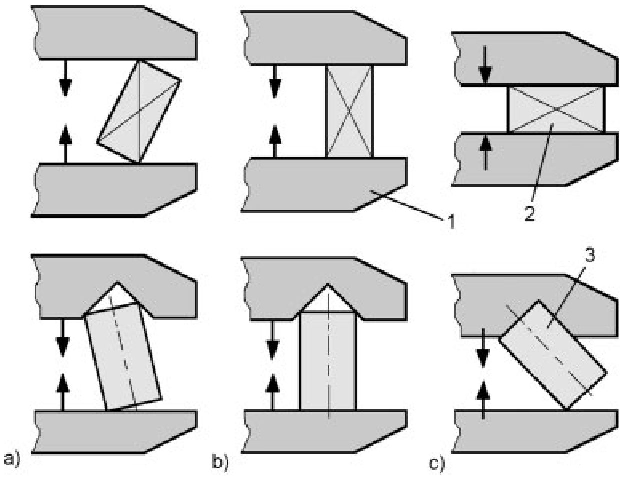
Fig. 2.20: Principles of "egg gripping"
a) direct two point impactive prehension
b) shape form impactive prehension
c) astrictive prehension
d) constrained capture

- Contigutive: force through direct contact, for example permatack adhesives, thermal (cryogenic or in some cases heating), liquid surface tension effects.

The most essential principles of a prehension strategy are schematically presented in Figure 2.20.

A firm grip of the object implies that direct contact has been already established between the gripper and workpiece in the primary phase of prehension. Direct contact is not necessary in the case of astrictive prehension, though in most cases it is desirable if only in the interests of eliminating orientation errors.

Mechanical impactive grippers exhibit errors related to their positioning by the handling equipment and the disposioning of target objects. These errors are normally allowed for, though there are situations which are not acceptable as the two examples shown in Figure 2.21 demonstrate. Friction is another important factor which can vary from workpiece to workpiece.



1 gripper finger
2 cuboid object
3 cylindical object

Fig. 2.21: Dislocation of the workpiece during prehension
a) contact phase
b) desired prehension position
c) wrong prehension position

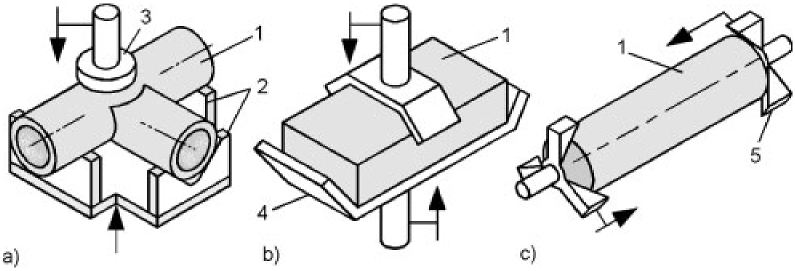


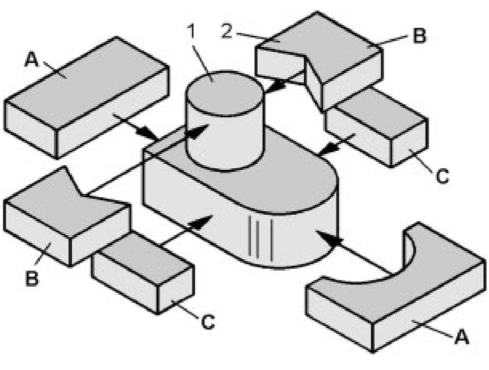
Fig. 2.22: Potential degrees of freedom *F* during prehension.
a) almost all possible degrees of freedom are suppressed, b) all possible degrees of freedom are suppressed, c) all but one possible degree of freedom are suppressed

How well a workpiece is secured in a gripping process depends on the number of degrees of freedom which are allowable following prehension.

As can be seen the gripper jaws can be adjusted to fit the workpiece geometry. In Figure 2.22 a only one degree of potential (rotational) freedom remains which is constrained to only a partial rotation. In Figure 2.22 b all 6 degrees of freedom are suppressed (ideal grip). For the example shown in Figure 2.22 c one full degree of freedom ($F = 1$) remains since the part can still rotate around its axis when the gripper jaws are closed.

Needless to say, the design of the gripper jaws also depends on the workpiece topology and in particular the exact prehension contour. Figure 2.23 illustrates an example of how a variation of two-finger grippers can be applied. In general surface contacts are more preferable than line or point contacts.

In reality objects, and particularly the materials from which they are made, are less than ideal. If the case of “plane parallel surfaces” is considered in closer detail it can be seen that the parallelism is not guaranteed at all for some workpieces, e.g. parts made from synthetic materials often exhibit deformations. If the deviations from a plane are relatively small, then the introduction of a surface compliance (soft rubber coatings on the gripper surfaces) usually suffices. However, in more extreme cases a pivoted jaw is more appropriate.



1 workpiece
2 gripper jaw

A shaped jaw/plane jaw
B prismatic jaw/prismatic jaw
C plane jaw/plane jaw

Fig. 2.23: The profile of the grip area determines the shape of the gripper jaws

The design of the gripper jaw also affects the choice of gripper. Formed jaws usually require longer travel and consequently larger stroke from the driving actuator. Consequently, it is important to decide whether axial or radial gripping is more appropriate. This is to a great extent dictated by logistical considerations. The example in Figure 2.24 illustrates such a problem. It shows how a parallel gripper with prismatic jaws is confronted with a larger range of travel when, a) grasping the object radially (from the side), and a much shorter range of jaw travel b) when gripping axially (from above).

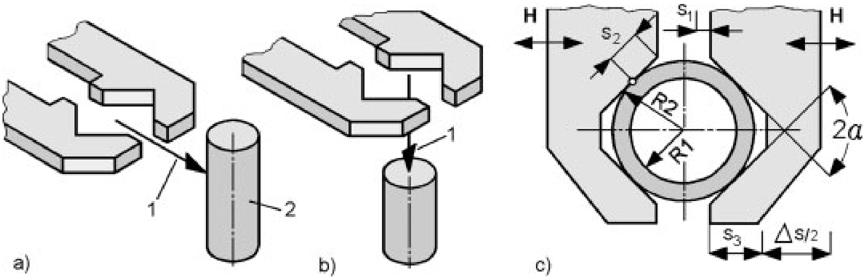


Fig. 2.24: Influence of the gripping strategy on the required opening width
a) radial gripping, b) axial gripping, c) gripper dimensions
1 direction of gripping, 2 gripped object
H opening width of the gripper jaws, *R* radius

Radial gripping: The following separation distances must be taken into account when gripping from the side:

S_1 play in jaw travel during enclosure
S_2 reliability tolerances for the contact points on large workpieces
S_3 play in jaw travel during opening (drive-in clearance)
S_4 maximum position deviation of the manipulator
S_5 maximum position deviation for provision of the workpiece
S_6 maximum position deviation of the gripper jaw caused by mechanical factors and fabrication tolerances
R_1 minimum radius size
R_2 maximum radius size

The opening width H is given by

$$H = R_2 + \frac{\Delta S}{2} + S_1 + S_3 + \left(\frac{R_2}{\tan\alpha} + S_2\right) \cdot \cos\alpha - \frac{R_1}{\sin\alpha} \tag{2.9}$$

The position deviation ΔS is obtained from the probability of individual deviations

$$\Delta S = k \cdot \sqrt{\Delta S_4^2 + \Delta S_5^2 + \Delta S_6^2} \tag{2.10}$$

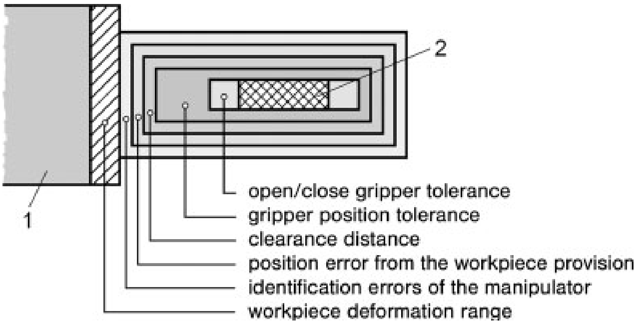
where k is a confidence or safety margin, for example 1.5

Axial gripping: A smaller jaw travel is sufficient in this case. For a double-prismatic gripper the opening width is given by

$$H = \frac{0{,}5 \cdot \Delta S + S_3 + R_2 - R_1}{\sin \alpha} + S_1 \tag{2.11}$$

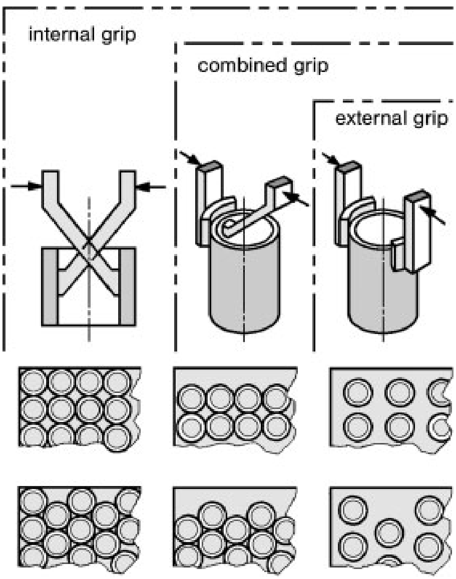
For a better understanding Figure 2.25 illustrates the specified errors and tolerances of gripper systems in a more general form. Further relationships can be obtained depending on the type of prehension (internal, external, combined grip etc.) and the gripper design. This will be described in the following:

Suitable gripping strategies for a range of magazine configurations are shown in Figure 2.26. The internal grip is applicable to all such possibilities, without special requirements. In the case of cylinder wall prehension (combined grip), space must be available to allow the gripper fingers to affect prehension externally.



1 workpiece
2 gripper jaw

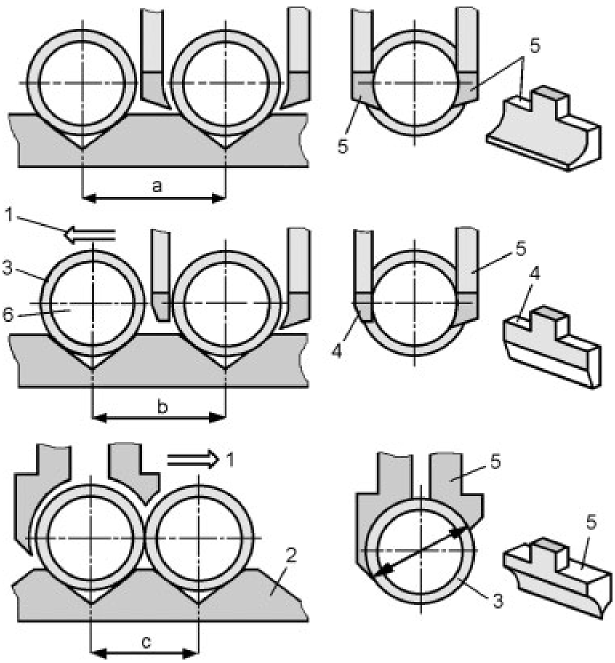
Fig. 2.25: Schematic representation of the errors related to the object provision and gripping point



Internal grip: applicable to all configurations shown
Combined grip: applicable to the middle and right configurations
External grip: applicable only for configurations with sufficient free space

Fig. 2.26: Workpiece magazine configurations and possibilities of trouble-free gripping

Complete external prehension requires even more space around the objects and as a result the storage density may be reduced. Consequently, either the way in which the objects are delivered must be changed or another gripping strategy chosen. This will be demonstrated by the following example: Metal shafts are presented parallel to onanother in a hard rubber pallet with prismatic furrows. What would be the optimum jaw design for such an application?



1 prehension sequence
2 furrowed pallet
3 synthetic protective cladding at shaft ends
4 smooth gripper jaw
5 shape mating gripper jaw
6 gripped object, finished shaft

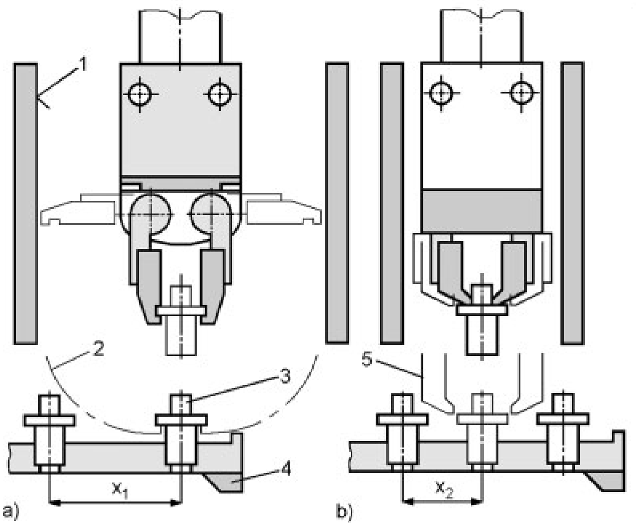
a, b, c axial shaft separation in the magazine

Fig. 2.27: Gripping of shafts from pallet

Should the workpieces be arranged so close to oneanother that there are no gaps between them, then it is only possible to grip the part lying at the end. The gripper jaws must be so designed that one contact is made under the horizontal centreline. The other contact is then made above the horizontal centreline thus ensuring that the direction of retention force passes diagonally through the object centrum. As can be seen from Figure 2.28 the necessary free space around the gripper also depends on its type and design. Opened gripper jaws can require excessive movement space. The use of a parallel gripper (b) allows for a smaller object separation x_2 in the magazine, in comparison to the object separation x_1 in the case of the angular gripper (a). This has the advantage of allowing increased storage density.

Where precise prehension is concerned it is essential to know whether deviations in object diameters also lead to displacement of the grip centre G. Depending on the gripper kinematics such displacements can take place along one or several axes. The differences between aligning, centring, and differentiating (creating deviations) forces are illustrated in Figure 2.29. Moreover, centring grippers can provide:

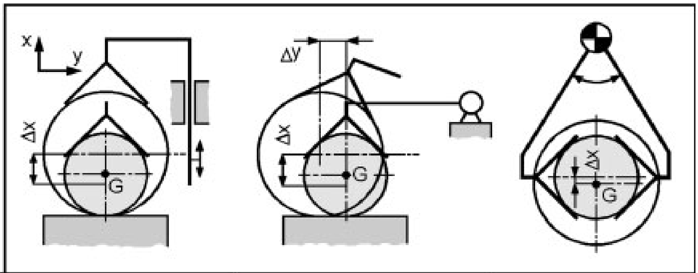
- point centring: $\Delta x = 0$ and $\Delta y = 0$
- axis centring: $\Delta x = 0$ or $\Delta y = 0$



1 obstacle edge
2 gripper jaw trajectory
3 gripped object
4 magazine
5 opened gripper jaw

x storage space separation

Fig. 2.28: Different gripper designs also present different obstacles.
a) angle gripper
b) parallel gripper



X	aligned	differentiating	differentiating
Y	centred	differentiating	centred

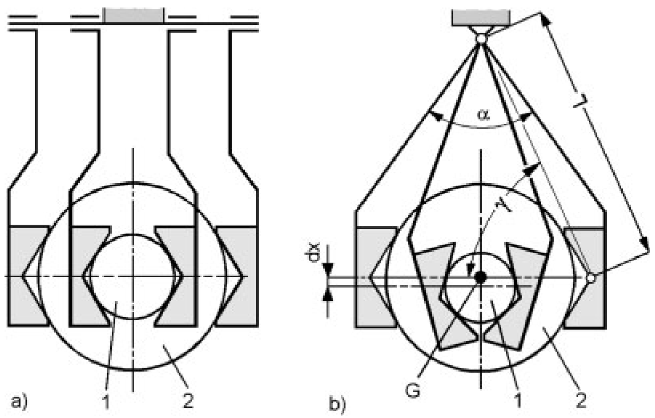
Fig. 2.29: Displacement of the prehension centre in the case of a prismatic gripper

The situation is different in cases concerning parallel jaw grippers (Fig. 2.30 a). They tend to automatically centre by nature of their prismatic mechanics. A similar situation is found with three-finger grippers and drill chucks. In the case of angular trajectory gripper jaws it is possible to compute the deviation from the grip centre, and hence the prehension accuracy.

The expression for *dx* is:

$$dx = L \cdot \sin\gamma \left(\frac{L}{\sin(0{,}5 \cdot \alpha + \gamma)} - 1 \right) \tag{2.12}$$

L distance from the rotational centre to the prismatic centre
α finger opening angle
γ angle imposed by gripper design



1 small diameter work-piece
2 large diameter work-piece

G prehension centre

Fig. 2.30: Prehension accuracy of an angular gripper
a) parallel gripper, b) angular (shear) gripper

Where the prism possesses a special profile (Fig. 2.31), an angular gripper with prismatic jaws is capable of compensating for central point displacements of workpieces with varying diameters. The following dimensioning should be taken into account:
- The ratio of the maximum (D_1) and minimum (D_2) diameters should not exceed ≈ 2.5.
- The contact angle α should lie between 40° and 50°.

The dimensions of the gripper jaws can then be calculated from:

$$D = \frac{(D_1 + D_2)}{2} \tag{2.13}$$

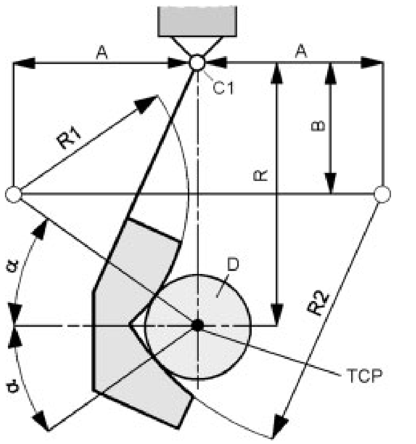
$$A = \frac{R}{2} \cdot \text{cotan}\,\alpha \tag{2.14}$$

$$B = 0.5 \cdot R \tag{2.15}$$

$$R1 = (R \cdot \sin\alpha) - \frac{D}{2} \tag{2.16}$$

$$R2 = (R \cdot \sin\alpha) + \frac{D}{2} \tag{2.17}$$

If the gripper is to be designed to avoid shear forces which may introduce centring errors, then an angle gripper with separated centres of rotation C1 and C2 for each finger is more applicable. This leads to an increase in $R1$ and a decrease in $R2$. The resulting angle between the lines TCP-C1 and TCP-C2 should lie between 0 and (2α – 40°) [2-14].



A, B distances from gripper pivot point
R radius from pivot point to workpiece centre
D workpiece diameter

Fig. 2.31: Prismatic jaw shape exhibiting centring

The displacements of prehension centre points for a gripper with rotational movement of the gripper jaws are illustrated in Figure 2.32. Although the prismatic jaws close parallel to one another, the centring effect concerns only one of the axes.

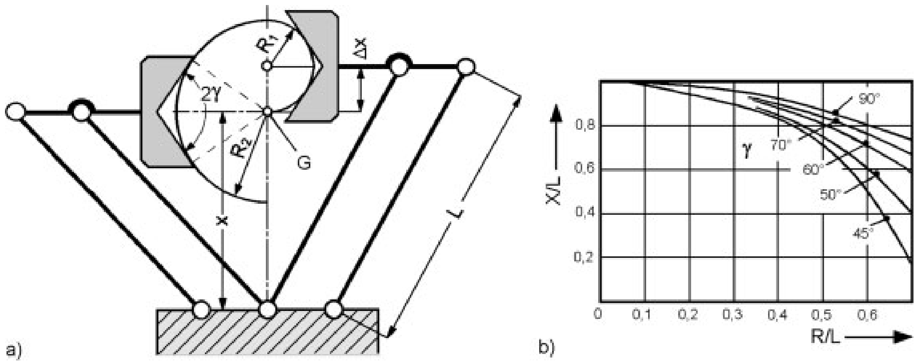


Fig. 2.32: Displacement of the prehension centre for a prismatic jaw gripper with circular translation
a) dimensional proportions,
b) dependence of the displacement on the prism angle

Whereby, for Figure 2.32:

γ half prism angle
L finger length
R_i workpiece radius
G prehension centre
x distance to prehension centre
Δx displacement of the prehension centre

The absolute value of the prehension centre displacement is obtained from

$$|\Delta x| = \frac{\sqrt{L^2 \cdot \sin^2\gamma - R_1^2} - \sqrt{L^2 \cdot \sin^2\gamma - R_2^2}}{\sin\gamma} \tag{2.18}$$

The previous analysis refers to shear grippers, i.e. grippers the fingers of which possess a common centre of rotation. The rotation centres of the fingers for the gripper depicted in Figure 2.33 are offset at a distance h from the geometrical centre.

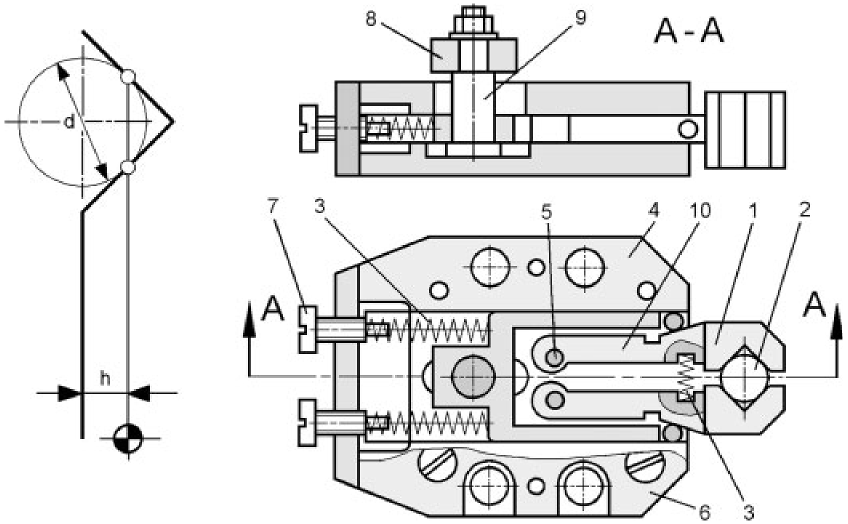
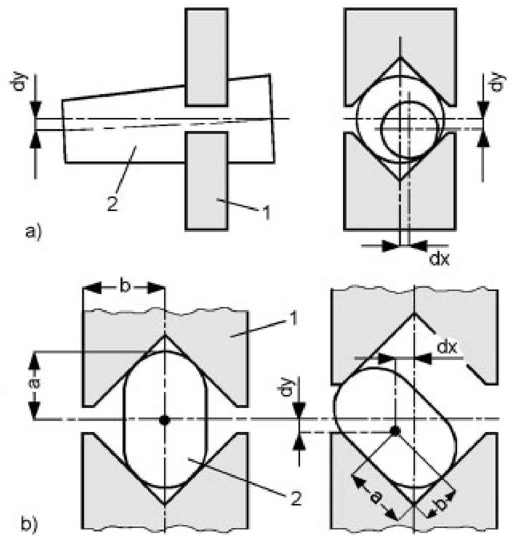


Fig. 2.33: Gripping unit for an assembly robot
1 gripper jaw, 2 workpiece, 3 return spring, 4 base plate, 5 axis pin, 6 cover plate, 7 spring force setting, 8 roller, 9 roller shaft, 10 gripper finger

If h also corresponds to the distance between the workpiece centrum and the finger contact points, this leads to a negligibly small centre point displacement Δx. Gripper closure is ensured by spring (3) return forces and opening proceeds via the displacement of the framework against and the spring forces and roller (8). The separation h of the gripper finger from the gripper axial centre is obtained from (2.19).

$$h = \left(\frac{d}{2} - \Delta d\right) \tan\frac{\alpha}{2} \tag{2.19}$$

d workpiece diameter
α prismatic opening angle
Δd workpiece tolerance (deviation in workpiece diameter)



1 prismatic gripper jaw
2 workpiece

dx, dy axis displacements
a, *b* object dimensions

Fig. 2.34: Workpiece centre displacement
a) conical component
b) elliptic component

Additional precision errors result from deviations in workpiece shape. These can result from conical (Fig. 2.34 a) and elliptical object shape variations (Fig. 2.34 b). Both lead to displacement of the workpiece centre in the axial directions x and y. Although these displacements are normally rather small, they can become very important in automatic mounting, particularly where long component parts are concerned.

Determination of achievable positioning accuracy can be a demanding objective in automation planning. A tolerance analysis is necessary to determine accuracy specifications for all equipment involved in mating tasks. If improvements are necessary they can sometimes be realised by design modifications to the product (fits, bevels, centring aids etc.), or by additional measures concerning the assembling equipment (mechanical or sensory).

It is obvious that workpiece position displacements can also result from defects in the gripping system caused by manufacturing errors or wear. Angular and translational examples in Figure 2.35 illustrate these problems.

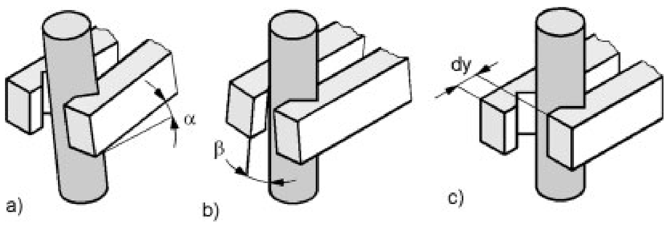


Fig. 2.35: Deficient gripping systems lead to position errors.
a) finger skew tilted, b) finger parallelism error, c) lateral displacement of finger

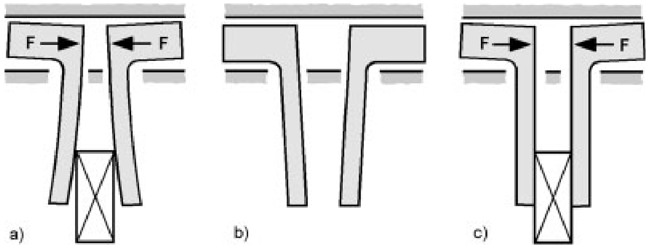


Fig. 2.36: Loss of parallelism with long fingers and large gripping forces [2-15]
a) gripping position for precisely right-angled fingers, b) preshaped fingers in unloaded state, c) gripping procedure for a gripper with preshaped fingers, *F* gripping force

Imperfections in gripper finger form can lead to poor surface contact with the object. This becomes particularly apparent where long fingered grippers of the types shown in Figure 2.36 a are employed.

The gripper fingers can be fabricated with an exactly calculated “preshaping”. In their unloaded state (Fig. 2.36 b) they no longer close parallel to one another. However, when loaded (Fig. 2.36 c), they provide a reliable surface contact with the object and undue displacements can be avoided. More practical is the introduction of compliance (see Fig. 13.15). If potential degradation (scratches) of the workpiece surface can be tolerated then the prehension area may be reduced and jaws which ensure non-slip prehension through microshape matching or clamping tips used (see Fig. 13.27).

“Design for assembly” and “design for automation” are strategies which make manufacturing quicker and easier. The change from lead through to SMD in the electronics industry is but one example. Unfortunately this is not always practical or cost effective and so the extent to which a product can be modified to fit a particular assembly plan is limited [2-16]. Consequently, necessary modifications are isolated to the handling equipment and some stimulating suggestions for the matching of grippers and objects are presented in Figure 2.37.

Design norms correspond to a great extent to workpiece design and for jig making. Examples include:
- shape matching,
- effect of the centre of gravity,
- transmission of force.

The design of a gripper system is influenced significantly by the forces necessary to ensure reliable prehension of the object. However, the required gripping force depends on many factors which can be only partially estimated. Some of them are:
- The spatial settings, i.e. the arrangement of the gripper relative to the industrial robot and its movable axes.
- The resultant force as a vector sum of all single acting forces resulting from mass, inertia, Coriolis and centrifugal forces – all of which may change with robot movement.
- Geometry of the object and particularly the prehension points – for example, in applications like the demoulding of cast parts.

- Design of the gripper jaws and the contribution of force and shape mating during individual motion phases.
- The material and surface of the gripper jaws (friction linings, adhesion pads, microtips etc.) and prehension points.
- Environmental and temperature dependant effects, such as oil, dust and other contaminants.

Vibration, caused by movement of the robot, can have the effect of modifying friction conditions resulting in a reduction in prehension force. This is particularly apparent in the

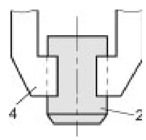
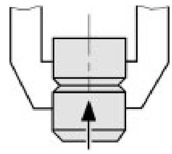
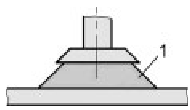
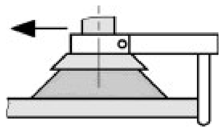
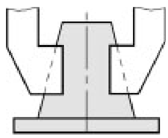
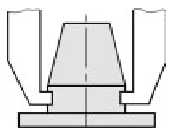
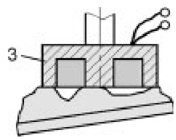
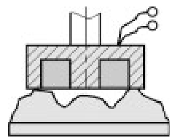
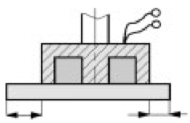
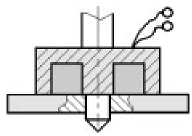
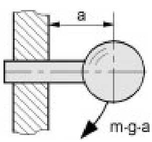
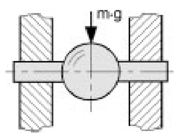
explanation	unfavourable	better
Shape matching allows for better transmission, e.g. of impactive forces, than pure force matching.		
Oiled steel sheets can slip from a rapidly moving transverse suction head if a constraint is not provided.		
Parallel prehension areas are always better and where possible should be deliberately formed on the workpiece.		
Astrictive prehension of, for example castings, requires a high degree of surface contact.		
Centring elements, e.g. bolt and holes, can be added to ensure improved prehension with astrictive methods.		
The centre of gravity of the component should lie between the gripper jaws so that there are no tilting moments M leading to displacement ($M = m \cdot g \cdot a$).		

Fig. 2.37: Examples for optimum prehension settings
1 suction head, 2 workpiece, 3 electromagnet, 4 prismatic jaw,
M moment, *m* mass, *g* acceleration due to gravity

case of sensitive thin-walled parts or in the finger guide ways of non-precision grippers without smooth running spindle guide ways.

It is often assumed that the increased number of gripper fingers results in a proportional increase of the prehension force. This interpretation is incorrect because it violates the law of interaction. This principle was precisely formulated by *Isaac Newton* (1643–1727) in 1687:

> Whenever one body exerts force upon a second body, the second body exerts an equal and opposite force against the first body.

This means that action and reaction are in equilibrium. A simple experiment illustrating this is presented in Figure 2.38. The tension of a rod is tested in two different ways. In the first case it is clamped and in the second case two persons are pulling the ends in opposite directions. The tensile force in the rod is not equal to 400 N, but in both cases amounts to 200 N. If this consideration is applied to the parallel gripper in Figure 2.38 b, it is clear that it makes no difference whether only one finger, providing a gripping force of 200 N, or two opposing fingers each applying 200 N are used. Both prehension strategies are equivalent in terms of the forces acting.

As will be seen later, the law of interaction, in a somewhat modified form, is also valid for three finger grippers with three directions of force. Initially, the forces occurring in a simple two jaw gripper will be considered.

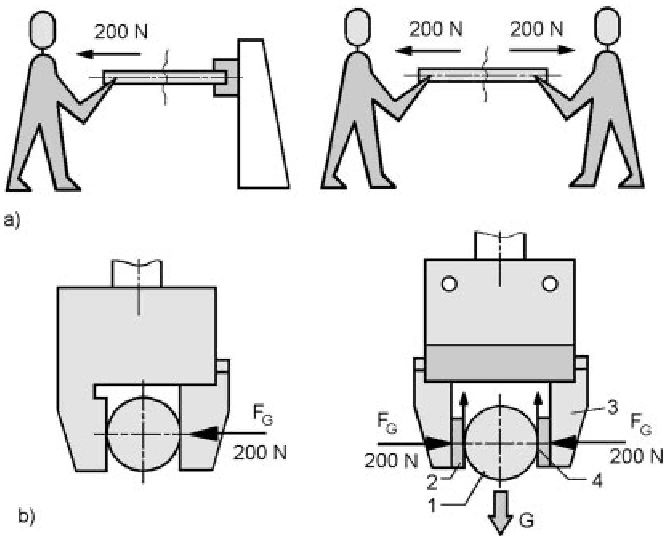
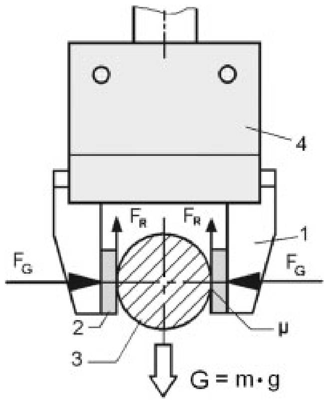


Fig. 2.38: Force interaction law
a) in both cases the tensile force within the rod amounts to 200 N
b) for a parallel jaw gripper, according to the *action = reaction* law, it is unimportant whether the force F_G is due to one or two fingers

Impactive grippers of the form shown in Figure 2.39, retain the object solely by frictional forces F_R. The gripping force F_G applied to the workpiece is given for a slow vertical motion (neglecting safety margins) by:

$$F_G = \frac{m \cdot g}{\mu \cdot n} \tag{2.20}$$

g acceleration due to gravity [m/s^2]
n number of fingers and jaws, respectively
μ friction coefficient between the gripper jaw and the workpiece

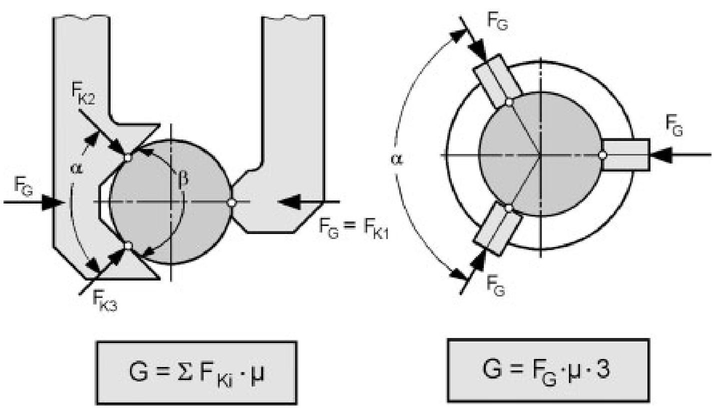


1 finger of a parallel jaw gripper
2 gripper jaw
3 workpiece

F_G gripping force (here also normal force)
F_R friction force
G gravitational force ($G = m \cdot g$)

Fig. 2.39: Forces acting on an object held at rest, and during motion

As can be seen, in the case of "dry friction" the friction forces F_R act according to the *Coulomb friction law* in a direction opposite to the motion. The number of fingers enters the equation because friction forces occur at every prehension interface. Thus, for a three finger gripper $n = 3$. At the same time it is unimportant if one deals with a "real" three finger gripper or a two finger gripper with a 3-point attachment (Fig. 2.40).



$G = m \cdot g$ gravitational force
F_G prehension force

Fig. 2.40: Plan view of two different three point prehension strategies
a) prismatic two finger gripper
b) three finger gripper

In the previously mentioned case, the gripping force F_G may be decomposed at the two contact point prism into contact forces F_{Ki}.

A two finger gripper is equivalent to a three finger gripper in terms of gripping force if it is designed with a prism angle of 120°, i.e. comparable with the finger settings of a three finger gripper. Of course, the situation is different for other prism angles. In such cases the contact forces must be considered and can be determined from the following relationship which is valid for any arbitrary prism angle:

$$F_{Ki} = \frac{m \cdot g \cdot \sin \alpha_i}{\mu \cdot (\sin \alpha_1 + \sin \alpha_2 + \sin \alpha_3)} \tag{2.21}$$

where $i = 1, 2, 3$ and $\alpha\,1 = 180° - \alpha_{23}$; $\alpha_2 = 180° - \alpha_{13}$; $\alpha_3 = 180° - \alpha_{12}$

The sum of the three frictional forces F_{R1} to F_{R3} (Fig. 2.41) must be at least equal to the gravitational force G. In cases concerning the handling of delicate objects, the surface contact point forces must also be considered.

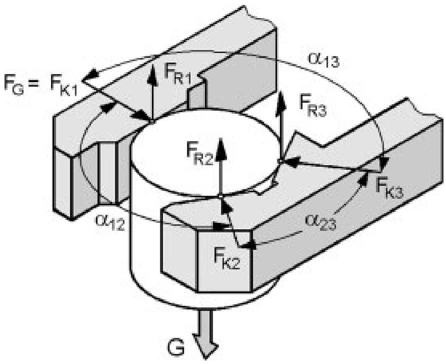


Fig. 2.41: Calculation of contact forces in the case of a gripper with half-sided prism

The coefficient of friction μ is dependant on both interface materials together with their respective lubricants (if any):

		Workpiece surface				
		Steel	Lubricated steel	Aluminium	Lubricated aluminium	Rubber, plastics
Finger surface	Steel	0.25	0.15	0.35	0.20	0.50
	Lubricated steel	0.15	0.09	0.21	0.12	0.30
	Aluminium	0.35	0.21	0.49	0.28	0.70
	Lubricated aluminium	0.20	0.12	0.28	0.16	0.40
	Rubber, plastics	0.50	0.30	0.70	0.40	1.00

The coefficient of friction μ for other material combinations can be found in [2–17]:

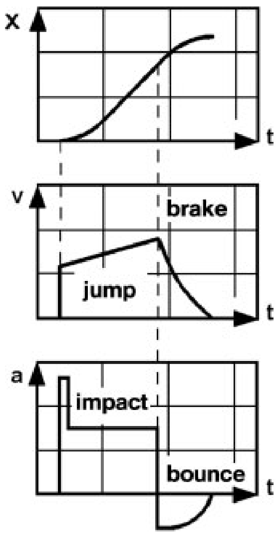
- Steel on typical (dry) bearing metals, e.g. bronze 0.10 to 0.5
- Steel on gemstone, e.g. sapphire or diamond 0.10 to 0.5
- Ceramics on ceramics, e.g. carbides 0.05 to 0.5
- Polymer on polymer 0.05 to 1.0
- Metal/ceramics on polymer, e.g. PE, PTFE, PVC 0.04 to 0.5
- Metal on metal (lubricated with graphite) 0.05 to 0.2

The choice of the safety margin depends on the type of the motion performed by the robot. The following rules of thumb normally apply:

- Safety factor of 2 for normal applications.
- Safety factor of 3 for motion in several axial directions with low acceleration and braking deceleration.
- Safety factor of 4 for large acceleration and braking deceleration and sudden impacts.

The terms "impact" and "bounce" during a gripping cycle are explained in Figure 2.42 [2–18].

The ensemble of forces acting on a gripper changes as acceleration takes place. One distinguishes between rotation and translational motion (in Figure 2.43; forces resulting from the Coriolis effects are not included here).



motion	impact	bounce
path x	brake	tangential transition
velocity v	jump	brake
acceleration a	Dirac impulse	jump

Fig. 2.42: Definition of the motion related effects "impact" and "bounce"

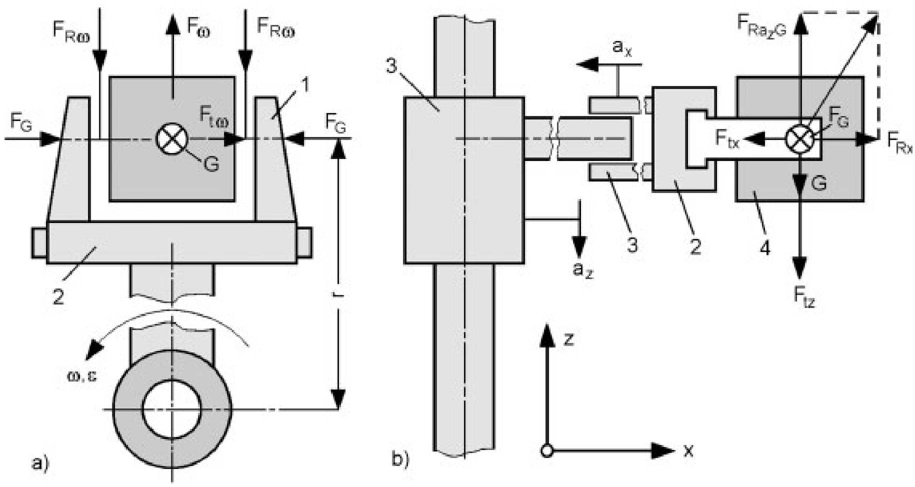


Fig. 2.43: Forces transmitted at the gripper jaw
a) rotational motion (plan view), b) translational motion (side view)
1 gripper jaw, 2 gripper, 3 translational axis, 4 workpiece

The notations used in the figure have the following meanings:

F_G prehension force
F_R frictional forces ($F_{R\omega}$ due to pivotal motion, F_{Rx} due to translational motion in the x-direction, F_{RazG} due to acceleration of the workpiece mass in the z-direction)
F_t inertial force
F_ω centrifugal force
G gravitational force on workpiece mass m
ω angular velocity
ε angular acceleration
r distance from the pivot centre to the workpiece
α acceleration (α_x in the x-direction, α_z in the z-direction)

The forces acting on a workpiece manipulated by a robot with two translational axes (x, y) and one rotation about the z axis are:

- Rotational inertia (centrifugal force) about the z-axis pivot

$$F_\omega = m \cdot r \cdot \omega^2 \tag{2.22}$$

- Inertial forces in the x-direction owing to the translational motion in x

$$F_{tx} = m \cdot \alpha_x \tag{2.23}$$

- Inertia forces due to acceleration about the z-axis pivot

  $$F_{t\omega} = m \cdot r \cdot \varepsilon \tag{2.24}$$

  or to the Coriolis acceleration as a result of simultaneous rotational and translational motions.
- Inertial forces in the z-direction in the case of accelerated vertical motion

The inertial forces F_{tx} and F_{tz} act in the directions shown for deceleration and in the opposite directions for acceleration. For the sake of clarity it will be assumed that the centre of mass is aligned with the gripping force centrum so that rotational motion of the gripper around the x-axis may be ignored.

Considering the effects of frictional forces:

$$F_R = \frac{m}{2}\sqrt{r^2 \cdot \omega^4 + g^2} \tag{2.25}$$

The required gripping force is obtained from

$$F_G = \frac{m}{2 \cdot \mu}\sqrt{r^2 \cdot \omega^4 + g^2} + m \cdot r \cdot \varepsilon \tag{2.25}$$

The friction $F_{t(\omega)}$ is effective only during such phases in which the rotational motion is decelerated from some high angular velocity. The centrifugal force is rather small in the case of rotational acceleration.

The nomograph presented in Figure 2.44 can be used for estimating the required prehension force (in accordance with the settings shown in Figure 2.43) [2-19].

In order to obtain the necessary driving force for the gripper jaw, transmission factors of the corresponding gears must also be taken into account. For example, lever gears operating in accordance with the knee lever principle exhibit high force amplification over only a very narrow range. Finally, in practice a safety margin must also be included.

Use of the nomograph: The nomograph consists of two graphs which are to be used together as will be explained by means of an example:

Example 1: Determine the necessary gripping force for the following parameters:
- workpiece mass $m = 0.45$ kg
- friction coefficient $\mu = 0.1$
- angular velocity $\omega = 3.3 s^{-1}$
- pivoting radius $r = 0.550$ m

Procedure: determine the intersection point of r and ω in the lower graph; draw an auxiliary line from this point to the origin 0; draw a horizontal line parallel to the F_R-axis from the corresponding mass value on the ordinate and then a vertical line from the intersection point upwards to the appropriate friction coefficient value in the upper graph (in this

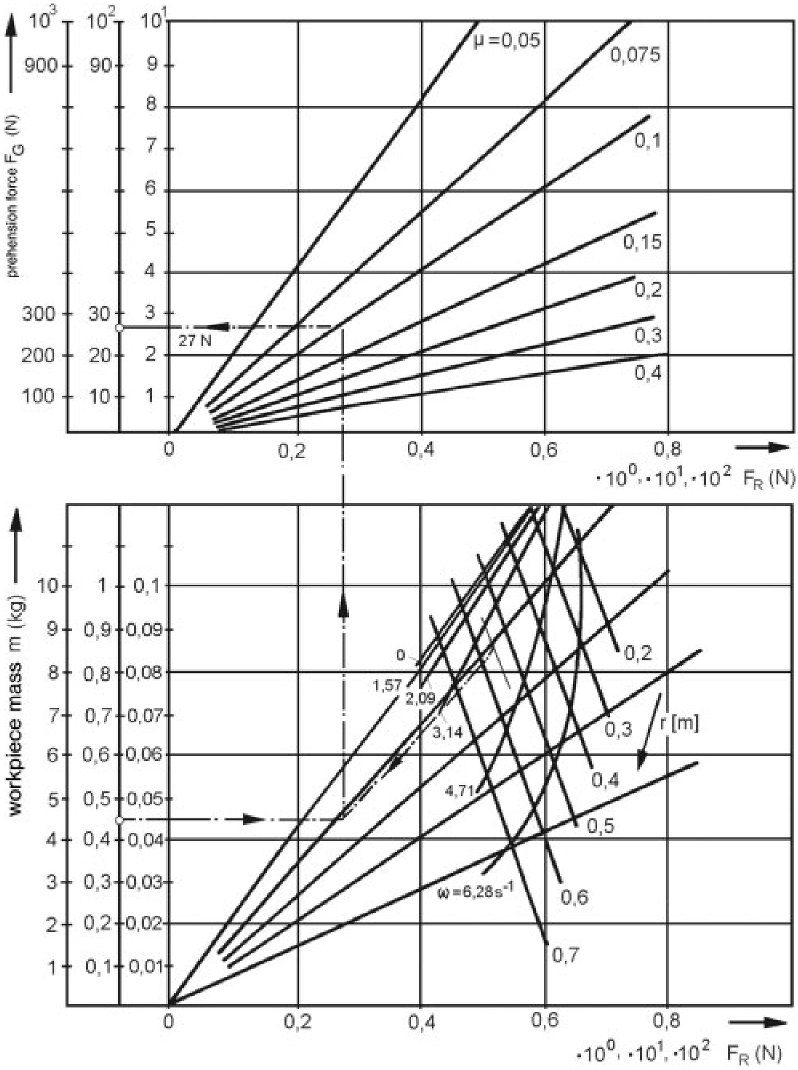


Fig. 2.44: Nomograph for estimation of prehension forces dependent on the workpiece mass *m*, the rotational radius r of the robot and the angular velocity omega

example, the line corresponding to $\mu = 0.1$); another horizontal line from this intersection point, parallel to the gripping force axis F_G, gives the value $F_G = 27$ N on the ordinate. A safety factor S can be also introduced, e.g.:

$$F_G = S \cdot 27 = 2 \cdot 27 = 54\,\text{N}$$

Example 2: Determine the upper limit for the angular velocity of an object undergoing manipulation according to the following technical specifications:

- gripping force $F_G = 350\,\text{N}$ (according to manufacturers specifications)
- friction coefficient $\mu = 0.1$
- pivoting radius $r = 0.6\ \text{m}$
- workpiece mass $m = 3\,\text{kg}$

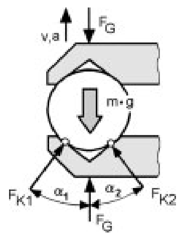
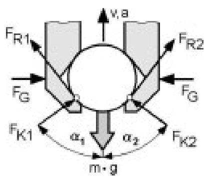
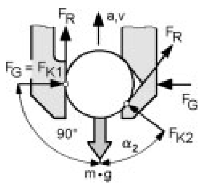
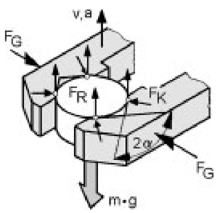
	sketch	contact forces	gripping force, upwards
shape force-mating		$F_{K1} = \dfrac{m(g+a)\sin\alpha_2}{\sin(\alpha_1+\alpha_2)}$ $F_{K2} = \dfrac{m(g+a)\sin\alpha_1}{\sin(\alpha_1+\alpha_2)}$	$F_G = m(g+a)\cdot S$
shape and friction mating		$F_{K1} = \dfrac{m(g+a)}{2\cdot\cos\alpha_1}$ $F_{K2} = \dfrac{m(g+a)\tan\alpha_2}{2\cdot\cos\alpha_2}$	$F_G = \dfrac{m(g+a)}{2}\tan\alpha\cdot S$
		$F_G = m(g+a)\tan\alpha_2$ $F_{K2} = \dfrac{m(g+a)}{2\cdot\cos\alpha_2}$	$F_G = F_{K1}\cdot S$
pure friction mating		$F_K = \dfrac{m(g+a)}{4\cdot\mu}$	$F_G = \dfrac{m(g+a)}{2\cdot\mu}\sin\alpha\cdot S$

Fig. 2.45: Forces acting in a parallel jaw gripper with double-sided or single-sided prismatic jaws for a linear motion [2-20]
a linear acceleration (recommended values: electrical shaft 6 m/s^2, electrical tooth belt 20 m/s^2, servopneumatic 25 m/s^2, pneumatic 30 m/s^2, pneumatic rotation or pivoting gears 40 m/s^2), g acceleration due to gravity, m mass, S safety factor, v velocity, μ friction coefficient

Draw a horizontal line in the upper graph from the value of 350 N to the intersection point with the $\mu = 0.1$ line. Draw a vertical line from this intersection point downwards in order to find the intersection point with the workpiece mass line corresponding to 3 kg. Draw an auxiliary line from the origin to the intersection point with the $r = 0.6$ line for the rotational radius. The resulting angular velocity is $\omega = 6.28\ \mathrm{s}^{-1}$. The angular velocity of the robot should not be allowed to exceed this value. Please remember, a safety factor has not been included in this second example.

The results obtained by the nomograph are only rough estimates but in most practical cases they are sufficient.

Figure 2.45 gives an overview with some typical impactive gripping examples.

If the workpiece is not held symmetrically, i.e. when the centre of mass does not correspond with the geometrical centre of the gripper, the forces acting on the gripper jaw pairs will not be equal. It is clear that, when selecting a gripper, one should take into account these effective forces or choose a more suitable prehension point so that the resulting moment of tilt is insignificant. Example cases are depicted in Figure 2.46.

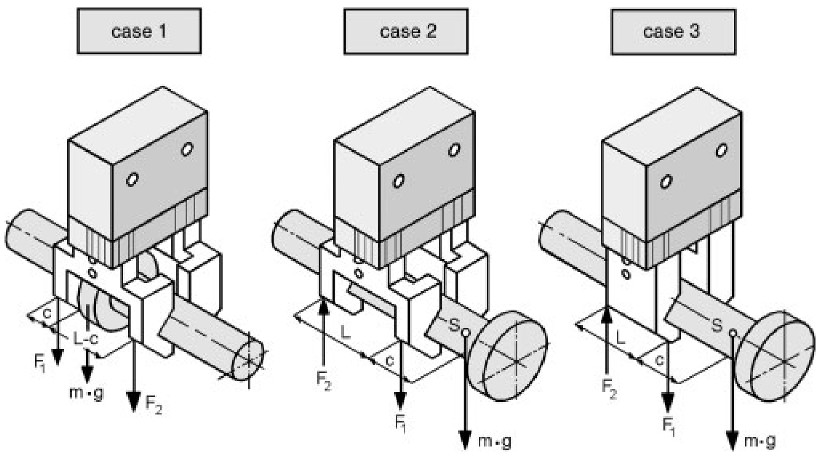


Fig. 2.46: Unsymmetrical force distribution on the gripper jaws
S mass centre of gravity

The following forces act on the gripper jaws:

Case 1:

$$F_1 = \frac{m \cdot g\,(L - c)}{L} \tag{2.27}$$

$$F_2 = \frac{m \cdot g \cdot c}{L} \tag{2.28}$$

Cases 2 and 3:

$$F_1 = \frac{m \cdot g\,(L + c)}{L} \tag{2.29}$$

$$F_2 = \frac{-\,m \cdot g \cdot c}{L} \tag{2.30}$$

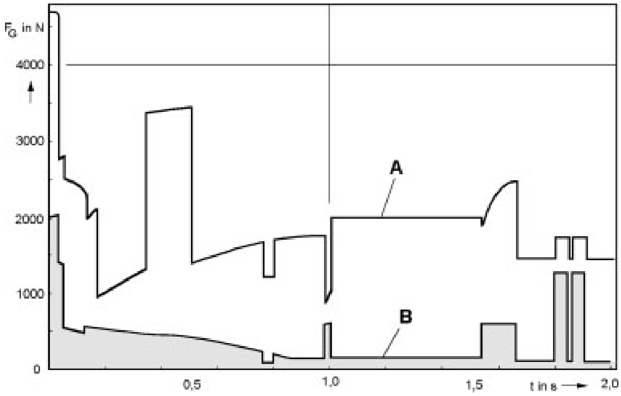
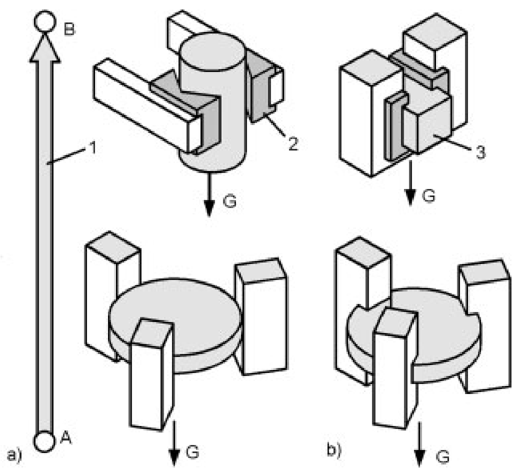


Fig. 2.47: Required gripping force during manipulation cycle
A: Time dependency of the retention force for prehension outside the mass centre of gravity
B: Requirements for the retention force for prehension within the mass centre of gravity

In reality, the required prehension forces are not constant but vary during the motion cycle. As a consequence, the necessary safety margin to ensure retention is also a variable. A reliable grip of the object is ensured when the exerted retention force F_{Gvorh}, which depends on the gripper design, exceeds the required retention force F_{Gerf} necessary to compensate for the forces due to object inertia and weight. The ratio of these two forces gives the necessary safety margin S

$$S = \frac{F_{\mathrm{Gvorh}}}{F_{\mathrm{Gerf}}} \tag{2.31}$$

The actual retention force required F_{Gerf} may be determined by analysing the motion of the gripper, in terms of velocity and acceleration (and their respective directions), throughout the work cycle. This is illustrated in Figure 2.47 using one example from [2–21].



1 direction of motion
2 gripper jaw
3 object

G gravitational force

Fig. 2.48: Management of motion force
a) force mating, b) shape mating

The prehension of workpieces outside the mass centre of gravity can lead to a considerable increase in the necessary retention force as a result of moment effects. All robot axes move simultaneously so the effects of individual moments cannot be ignored. In cases where it is possible to control the acceleration of the robot during run time (as is the case with most modern robot programming languages), the peaks in required retention force as depicted in Figure 2.47 may be compensated by reduced acceleration at these points.

Another possibility is to improve the shape mating between the gripper fingers and object topology. This is most important in the direction of the largest expected accelerations as illustrated in Figure 2.48.

2.2.3
Gripper Flexibility

The flexibility of a gripper is defined as its applicability to a range of tasks without manual hardware modification. More sophisticated examples include a degree of adaptability (hardware modification without human intervention) to object topology. The emulation of

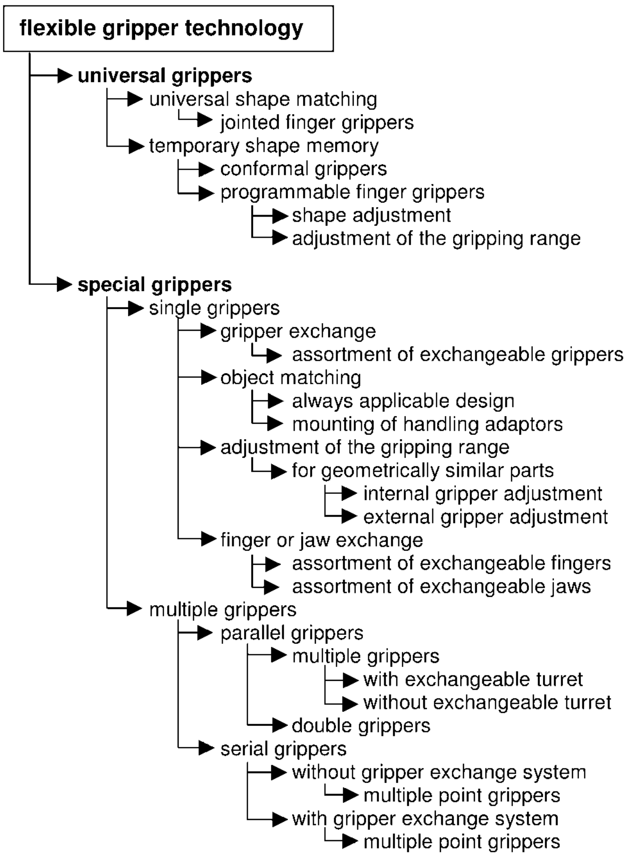


Fig. 2.49: Technical solutions to achieve gripper flexibility [2-22]

the human hand by so called “dextrous hands” (see Chapter 8) is interesting but has little industrial relevance. Such grippers deliver only limited force, are expensive, often slow and contain a large number of moving parts.

There are many ways by which flexibility can be achieved. Figure 2.49 provides an overview.

Flexibility is most often achieved through:
- Adding a degree of subsystem flexibility (physical stroke, prehension force, variable jaw geometry) to conventional grippers.
- Automatic exchange (tool exchanger or rotatable turret) of conventional single purpose grippers.

In some rare cases the objects can be unified by temporally equipping them with handling adaptors which offer a universal interface between the object and the gripper jaw. Sketches of revolver and multi-point grippers, as well as an exchanging system (see Chapter 12 for more specific details) can be seen in Figure 2.50.

Profile matching is the most frequently used method. Should the approximate object profile be known in advance then one of the following possibilities is likely to be applicable:
- Manual or automatic (rarely) exchange of gripper jaws (see Section 12.3.6).
- Shape adaptive or conformal grippers (see Fig. 13.20).
- Wide range grippers encompassing a broad spectrum of object dimensions (see Fig. 3.67).
- Multi-point grippers with several possible prehension points (see Fig. 2.51). Such grippers, with as many as 9 prehension points, have been developed for assembling purposes.

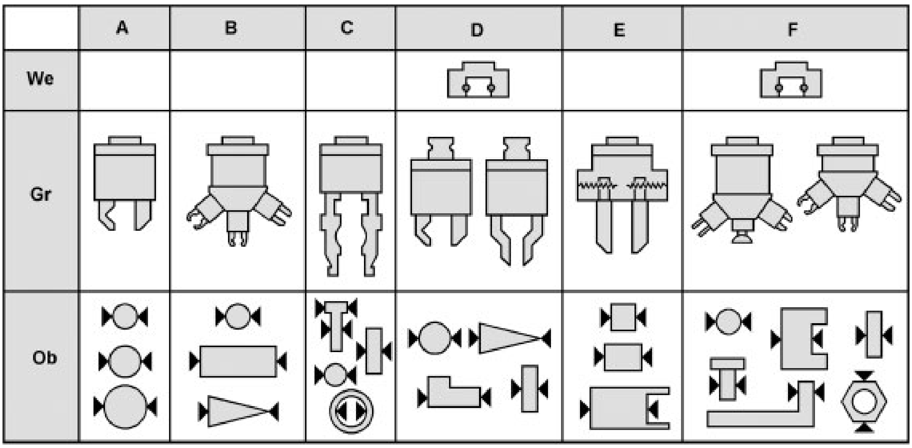


Fig. 2.50: Technical concepts of shape and size matching to objects
A simple impactive gripper, *B* turret, *C* gripper with multiple prehension points, *D* single grippers with exchange system, *E* gripper with controllable finger adjustment, *F* turret together with exchange system. We: exchange system, Gr: gripper, Ob: object

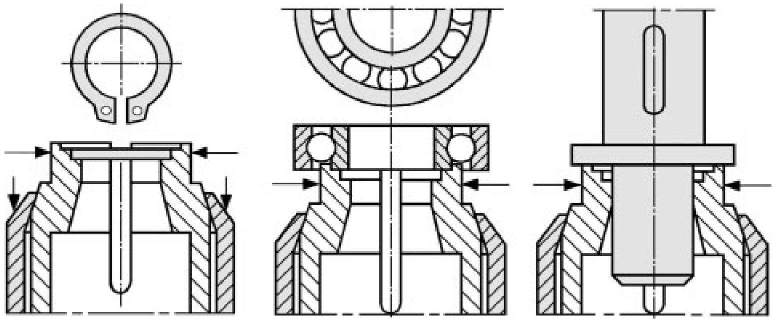


Fig. 2.51: Three function gripper for mounting operations

Many of the methods mentioned require a handling machine with smoothly programmable control in order to make use of the gripper flexibility. Sensory integration may also be used to improve the flexibility of the gripper. Such functions are, for example:

- Adjustment of the gripping force to the workpiece mass, e.g. by means of slip sensors (see Fig. 11.28).
- Additional gripper jaw rotation function (see Fig. 3.96).

One example of a multi-point gripper is shown in Figure 2.51. Depending on its position, this gripper can grasp a mandrel retaining ring, a ball bearing, or a gear shaft and install them onto the corresponding target location.

The technical efforts necessary to accomplish these three functions are relatively trivial. The gripper operates according to the impactive principle. The retaining ring is not directly connected but inserted initially into a fixture.

2.3 Gripper Classification

As previously mentioned, grippers may be categorised (in the broadest manner) in four main groups: Impactive (a direct mechanical force from two or mode directions is applied to the object), Ingressive (prehension of the object is achieved through permeation of the object surface), Astrictive (a binding force is applied in a single direction) and Contigutive (non impactive methods whereby a direct contact is required to provide a prehension force in a single direction). These four categories, together with typical examples, are listed in the table given in Figure 2.52.

The majority of industrial grippers are either of the impactive kind, to which the greater part of this book is devoted, or of an astrictive nature (particularly vacuum suction). Nevertheless, many other designs using the methods given above do exist and will be explained in due course.

The ingressive grippers may be subdivided into a further two categories; those which permeate the material (intrusive) and those which do not. Most needle based grippers and deliberately designed to penetrate the materials surface. Other methods, for example

Prehension method	Gripper type	Typical examples
Impactive		Clamps (external fingers, internal fingers, chucks, spring clamps), tongs (parallel, shear, angle, radial)
Ingressive	Intrusive	Pins, needles, hackles
	Non-intrusive	Hook and loop
Astrictive	Vacuum suction	Vacuum suction cup/bellows
	Magnetoadhesion	Permanent magnet, electromagnet
	Electroadhesion	Electrostatic field
Contigutive	Thermal	Freezing, melting
	Chemical	Permatack adhesives
	Fluid	Capillary action, surface tension

Fig. 2.52: Gripper classification according to their physical principle of operation

those based on hook and loop (Velcro) techniques do not. The specific choice of design depends largely on the material to be handled.

Similarly, there are three sub-groups for astrictive prehension. Although electroadhesion is suitable with almost all materials, both electrically conducting and non-conducting, it is limited to relatively light objects. Vacuum suction is also usable with almost any material and provides a much larger gripping force. However, a near perfect pneumatic contact is necessary. Magnetoadhesion also provides a very usable prehension force but is strictly limited to magnetically susceptible materials (Iron, Steel, Nickel and Cobalt).

Prehension method	Gripper type	Typical object materials
Impactive		Rigid objects
Ingressive	Intrusive	Flexible objects: textiles, carbon and glass fibre
	Non-intrusive	Flexible objects: textiles, carbon and glass fibre
Astrictive	Vacuum suction	Non-porous, rigid materials
	Magnetoadhesion	Ferrous materials
	Electroadhesion	Light sheet materials and microcomponents
Contigutive	Thermal	Flexible objects: textiles, carbon and glass fibre
	Chemical	Carbon fibre with glue impregnation
	Surface tension	Small, light objects (microcomponents)

Fig. 2.53: Gripper classification and suitability of object materials

Gripper	Material type	Example application
Spoon	Rigid	Loose materials such as nuts and bolts
	Flexible	Powders and viscous fluids
Hook	Rigid	Determinate topology for example castings
	Flexible	Waste materials sorting

Fig. 2.54: Other prehension methods not normally categorised

Other classification schemes proposed, for example [2-23] contain only three holding techniques. What is absent from most classifications are such everyday methods as spoon or hook. Whether these really constitute robot grippers in the conventional sense is debatable. However, for completeness they will be included. Figure 2.54 lists methods and applications for such grippers.

2.4 Requirements and Gripper Characteristics

The choice of a gripper depends mainly on the work it has to perform. Every prehension task is characterized by the following factors and requirements:

- **Technological requirements;** These include prehension time, gripping path, time dependence of the prehension force and the number of the object acquisitions per gripping cycle.
- **The effects of the prehended objects;** These include the mass, design, dimensions, tolerances, position of the centre of gravity, stability, surface, material, strength, and temperature. The correlations between gripper and object can be summarized as listed below:

object shape ⟺ gripping surface
object size ⟺ gripping range
object mass ⟺ gripping force
object position ⟺ gripping point

- **Factors related to handling equipment**, such as the positional accuracy, axial accelerations and connection specifications (mechanical, electrical, fluidic etc.).
- **Factors related to environmental parameters;** these include process forces, feeding conditions and clamps, storage conditions, contaminations, humidity and vibration.

The choice of gripping principle is based on the requirements and their analysis. There are many effects with complicated interrelationships and it is difficult to obtain a complete overview. A selection of them are presented in Figure 2.55 as a semantic network. A semantic network is a formalism for representation of knowledge in the form of a structure reflecting the interrelations among objects, which consists of nodes connected by directed paths. The nodes represent specific aspects of the gripper.

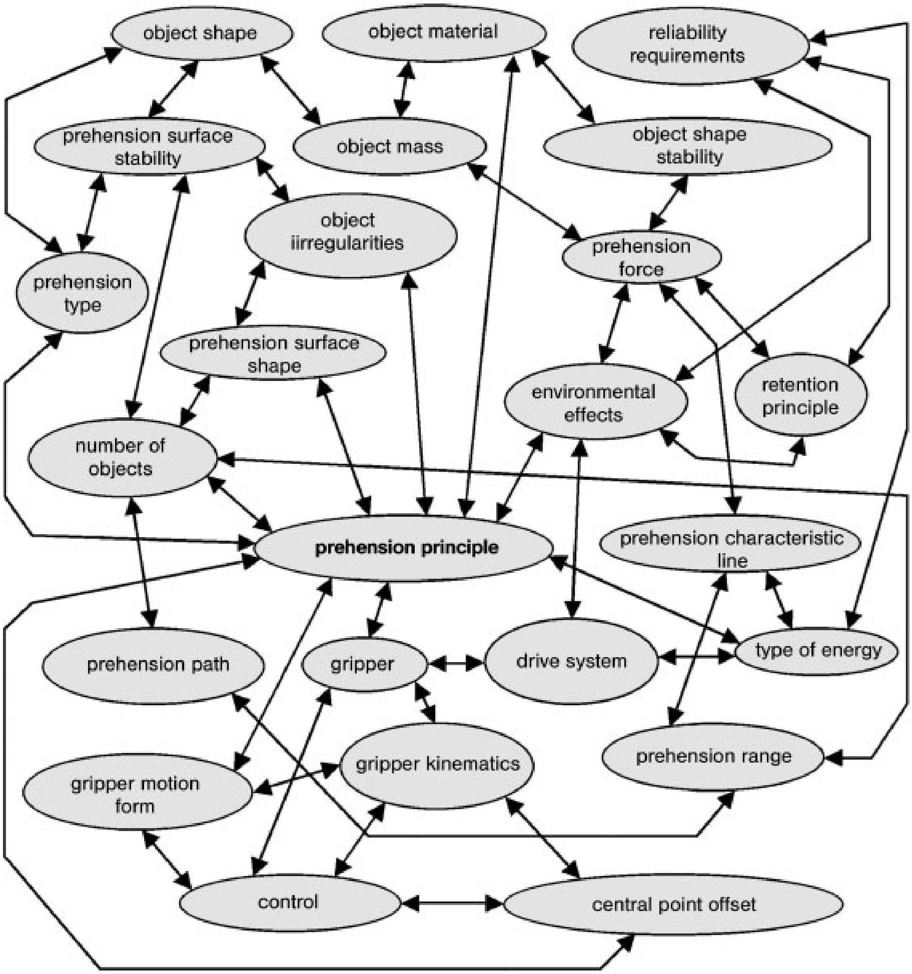


Fig. 2.55: Semantic network illustrating interdependences relevant to prehension principle selection [2-24]

A high quality gripper should possess the following properties:

- Optimum adjustment of the gripper structure to the operations performed.
- Large adjustment range and options to prehend parts of different shape and size.
- Reliability with respect to dislocations of the object (stability of the object position and orientation).
- Optimum gripping force path characteristics.
- Low number of links and joints (where applicable).
- Small installation space and mass, robustness.
- High reliability combined with easy service.
- Avoidance of damage and deformation to the object during prehension.

- Sufficiently high object positional accuracy.
- Good wear resistance.
- Simple control and short action times.

Some rather specific requirements include:
- Variation of prehension possibilities depending on object mass, shape and size.
- Possibility to selectively acquire objects in close proximity to one another.
- Rapid gripper exchange.
- Variation of the holding force dependent on the object mass.

The following table summarizes the most important gripper parameters:

<table>
<tr><td colspan="2">General specifications

❶ Type identifier, ❷ Class, ❸ Installation size</td></tr>
<tr><td>Primary characteristics</td><td>Secondary characteristics</td></tr>
<tr><td>Active principle
• mechanical
• fluidic
– compressed air
– vacuum
• magnetic
– permanent magnet
– electromagnetic
• adhesive
Prehension force [N]
Prehension force time dependence
Prehension force diagram
Prehension range per jaw [mm] or angle of spread [°]
Gripping range settings
Load bearing capacity max. [N]
Closing (prehension) time [s]
Opening (release) time [s]
Load limits
• forces
• moments of force
• finger length
Number of grasping organs
Overall dimensions [mm]
Deadweight [kg]</td><td>Environmental factors (cleanroom class)
• exhaust air
• abrasion
Bearing and guideway design
Model range selection
Operating temperature
Operation type
• single-acting
• double-acting
Power/mass ratio
Mass moment of inertia [kgm^2]
Reproducibility and accuracy [mm]
Operational pressure range [bar]
Maintenance cycle
Installation position
Maximum operational frequency [Hz]
Energy type and consumption
Retention force backup in case of energy failure
Monitoring of prehension range
Material specifications
Interface specifications
• mechanical
• fluidic
• electric
Service life</td></tr>
</table>

Gripper specifications for technical characterization

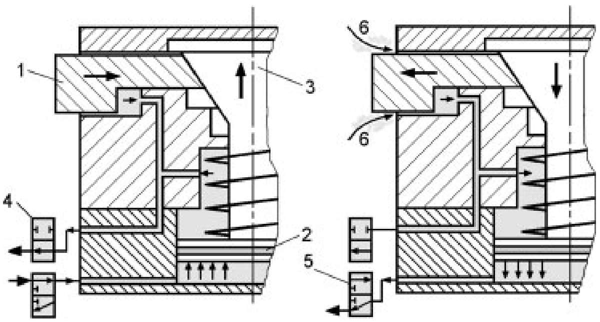
A particular requirement for all grippers which employ pneumatic, hydraulic or lubricated members are good seals. The portion of the cleanroom production is steadily increasing which places growing demand on the availability of grippers suitable for operation in such conditions. The following specifications concerning the feasibility can be found in the VDI (The German Engineering Institute): Guidelines 2083, Page 8 (cleanroom feasibility of manufacturing resources). The production branches and the critical particle sizes are:

• Fine mechanics	1 to 100 μm
• Printed circuit board manufacturing	5 to 50 μm
• Implant fabrication	5 to 20 μm
• Optical elements	0.3 to 20 μm
• Varnishing and medical technologies	5 to 10 μm
• Pharmaceutical	0.5 to 5 μm
• Microelectronics	0.03 to 0.5 μm

Grippers for "pure" manufacturing can be designed using two different strategies:

- Avoidance of contaminants using abrasion resistant materials for joints and guideways or by employing solid-state joints; use of brushless electric motors, polished external parts and stainless steel for fasteners; Avoidance of weld seams that are visible from outside.
- Elimination of contaminants using on-site extraction systems; seals with, e.g., Teflon bellows; sealing of threads (if necessary by cap nuts and gaskets); encapsulation of gears; laying of feed lines inside the gripper housing.

Figure 2.56 shows a patented gripper design which, on opening its jaws, produces negative pressure inside its housing, so that particles emerging through abrasion in the guide slide bearings cannot escape into the cleanroom. Guide slide bearings are in principle sources of such particles. The pump effect which takes place once per gripping cycle leads to a degree of self purification of the gripper's inner space.



1 basic jaw
2 pneumatic cylinder
3 wedged clasp
4 2/2-way valve
5 3/2-way valve
6 air suction

Fig. 2.56: Principle of a cleanroom gripper (*SCHUNK*)

The gripper jaws are not fully sealed with respect to the gripper guideway so that sufficient air may be sucked through the guideways. Products of abrasion and other contaminants are swept along the guideways and out through a 3/2-way valve.

Cleanroom classification, according to ISO 14644, specifies ISO 1 to ISO 9 in particles per m^3. ISO 8 corresponds to class 100.000 according to the now obsolete Standard US FS 209 E. The following table contains the number of particles of a given size per cubic meter as specified by the two standards.

Purity class according to ISO 14 644–1, (US Fed. 209 E)	0.1 µm	0.2 µm	0.3 µm	0.5 µm	1.0 µm	5.0 µm
	m^3	m^3	m^3	m^3	m^3	m^3
ISO 1	10	2	0	0	0	0
ISO 2	100	24	10	4	0	0
ISO 3 (1)	1 000	237	102	35	8	0
ISO 4 (10)	1 000	2 370	1 020	352	83	–
ISO 5 (100)	100 000	23 700	10 200	3 520	832	29
ISO 6 (1 000)	1 000 000	237 000	102 000	35 200	8 320	293
ISO 7 (10 000)	–	–	–	352 000	83 200	2 930
ISO 8 (100 000)	–	–	–	3 520 000	832 000	29 300
ISO 9	–	–	–	35 200 000	8 320 000	293 000

The human factor is one of the main contributors to contamination in cleanroom environments. Human skin surface, amounting on average to 1.75 m^2, is regenerated roughly every 5 days which means that, in the worst case, about 10 million particles per day are emitted.

2.5 Planning and Selection of Grippers

The choice of gripper is also dependant on availability, influencing factors include:
- The gripper must be selected from a commercially available assortment.
- The gripper must be custom designed according to requested specifications.
- The gripper may be assembled from construction kit components.

If a whole workpiece spectrum must be handled then the gripper selection begins with an analysis of the object and the process conditions. Some manufacturers offer free selection software which allows the computation of the technical/physical parameters. The scheme shown in Figure 2.57 reveals which factors significantly influence gripper selection. It is crucial to consider not only static, but also dynamic, conditions of a moving system. Moreover, it is not sufficient to consider some arbitrary moment during the handling cycle. Consequently, there are two possibilities:
- Mitigation of the requirements by modification of the motion parameters and the temporal constraints and/or
- Selection of a gripper according to the maximum values that occur within a complete handling cycle.

There is naturally a trade off between unnecessarily high requirements and reasonable financial factors. Control of robot speed and accelerations during run-time can help a lot in avoiding peak forces.

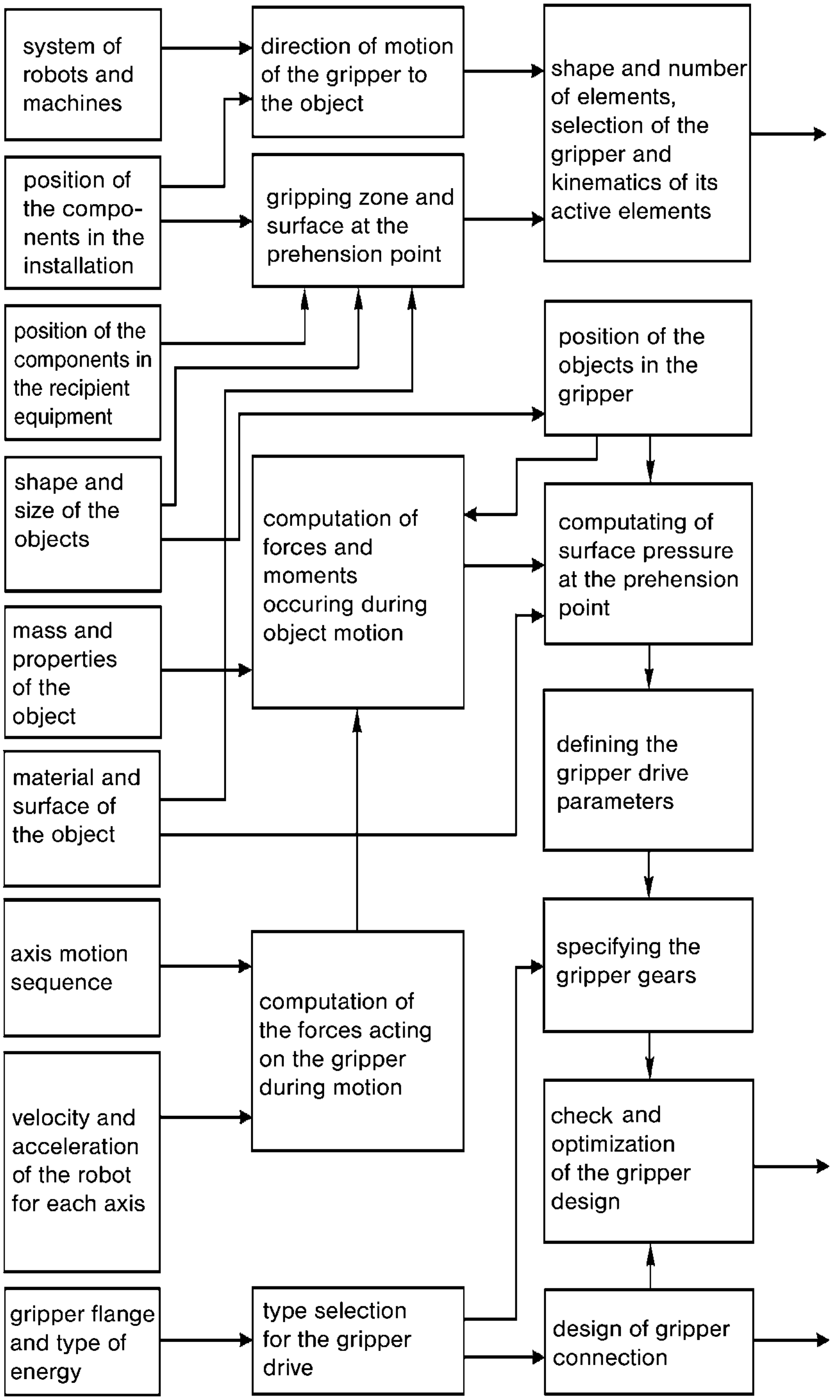
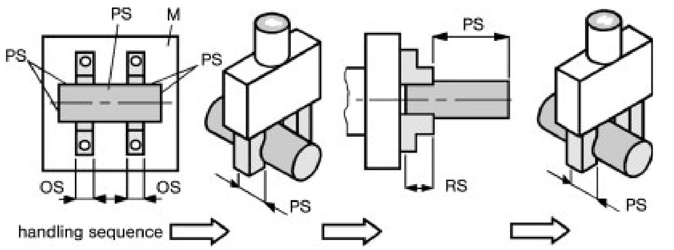


Fig. 2.57: Interacting factors and input parameters relevant to gripper design



OS overlay surface
PS prehension surface
RS retention-surface
M magazine

Fig. 2.58: The prehension surfaces PS cannot be arbitrarily set

Complicated workpiece geometry dictates the need for a more extensive analysis in finding the most suitable prehension points. It is often difficult to ascertain exact centres of gravity, especially with inhomogeneous objects formed from a mixture of dissimilar materials with different densities. Surface finishing or mechanical weakness at the geometrically optimal prehension points may rule out gripping in this region. Physical access or adequate approach paths to the geometrically optimal prehension points may be barred owing to constructional hindrances.

As already indicated (see Fig. 2.10), due to the nature of retaining mechanisms certain areas of even simple parts may not always be accessible for prehension. For example, *OS* in Figure 2.58 which are in partial contact with the support, cannot be used for gripping. Also the retention surfaces *RS* which are used when inserting the workpiece into the chuck are unavailable for prehension. The remaining surfaces that are suitable for gripping are designated as *PS* in Figure 2.58.

These are the characteristics of the object which are to come into contact with the gripper and ensure reliable prehension. Their counterparts are the gripper characteristics. In cases where the prehension surface pair has already been determined, the exact choice of gripper depends on commercial availability. In making this decision it is necessary to take into account several parameters, such as the size of the gripper inner surface relative to the size and mass of the object (prehension features). In addition, in case of force mating (as opposed to shape mating), the coefficient of friction between the gripper jaw and the workpiece must be considered (Fig. 2.59).

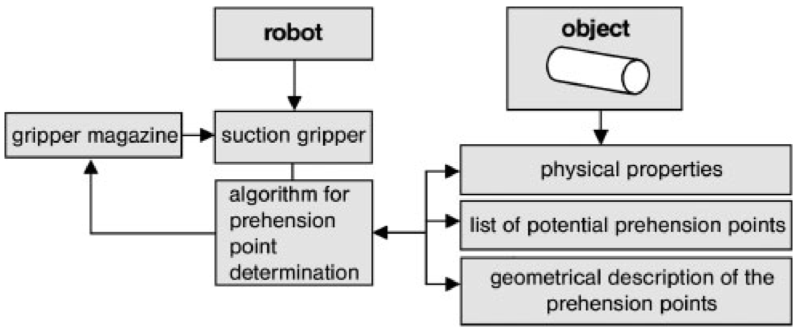


Fig 2.59: Diagram illustrating the automated determination of prehension points

physical principle		impactive mechanical				pneumatic	magnetic	
prehended object \ gripper type		parallel gripper	radial gripper	angle gripper	3 point gripper	suction gripper	permanent magnet	electro-magnet
mass	0.2 to 1 kg	▬	▬	▬	▬	▬	▬	
	1 to 10 kg	▬	▭	▬	▬	▬		
	10 to 50 kg	◧	▭	▬	▬	▬		▬
	heavier than 50 kg	▭		▬	▬	◧		
dimensions	20 to 50 mm	▬	▬	▬	▬	▬	▬	▬
	50 to 300 mm	▬	▭	▬	◧	▬	▬	▬
	300 mm to 1 m	▬		▬	▭	▬		▬
	more than 1 m	▬		▬		▬		▬
inner grip surfaces		▬		▭	▬			◧
surface	polished	▬	▬	▬	▬	▬	▬	▬
	rough	▬	▬	▬	▬			◧
	porous	▬	▭	▭	▭	▭		◧
	sensitive	▭			▭	▬	▬	▬
round parts	disk	◧	▬		▬	▬	▬	▬
	short cylinder	▬	▬	▬	▬	▬		▬
	shaft, rod	◧		▬				◧
prismatic parts	block part	▬	▬	▬		▬	▬	◧
	flat/short	▭	▬	▭		▬	▬	▬
	flat/long			▭		▬	◧	▬
synthetics		▬	▭	▭		▬		
textiles						▭		
foil						◧		
glass		▭	◧	◧	◧	▬		
stoneware		▭	◧	◧	◧	▭		
sheet metal		◧		◧		▬	▬	▬

Fig. 2.60: Rough classification of objects and the assignment of possible gripper types.
filled stripe = suitable; empty stripe = conditionally suitable

The simulation of gripping operations can be facilitated, e.g. by gripper libraries as the one available in the COSIMIR System which contains digitized (abstract) grippers.

The overview presented in Figure 2.60 can also be used for a rough preselection of impactive and some astrictive grippers. The use of impactive grippers can result in large surface pressures between the object and the contact points capable of causing damage to the object, e.g. scratches or dents in thin-walled hollow components. Consequently, in certain cases it is also necessary to evaluate the applied surface pressure.

When selecting a gripper the required functional capacity must also be considered. Increasing the functional density of a single robot workstation can result in considerable savings over the employment of multiple robot systems with distributed functionality.

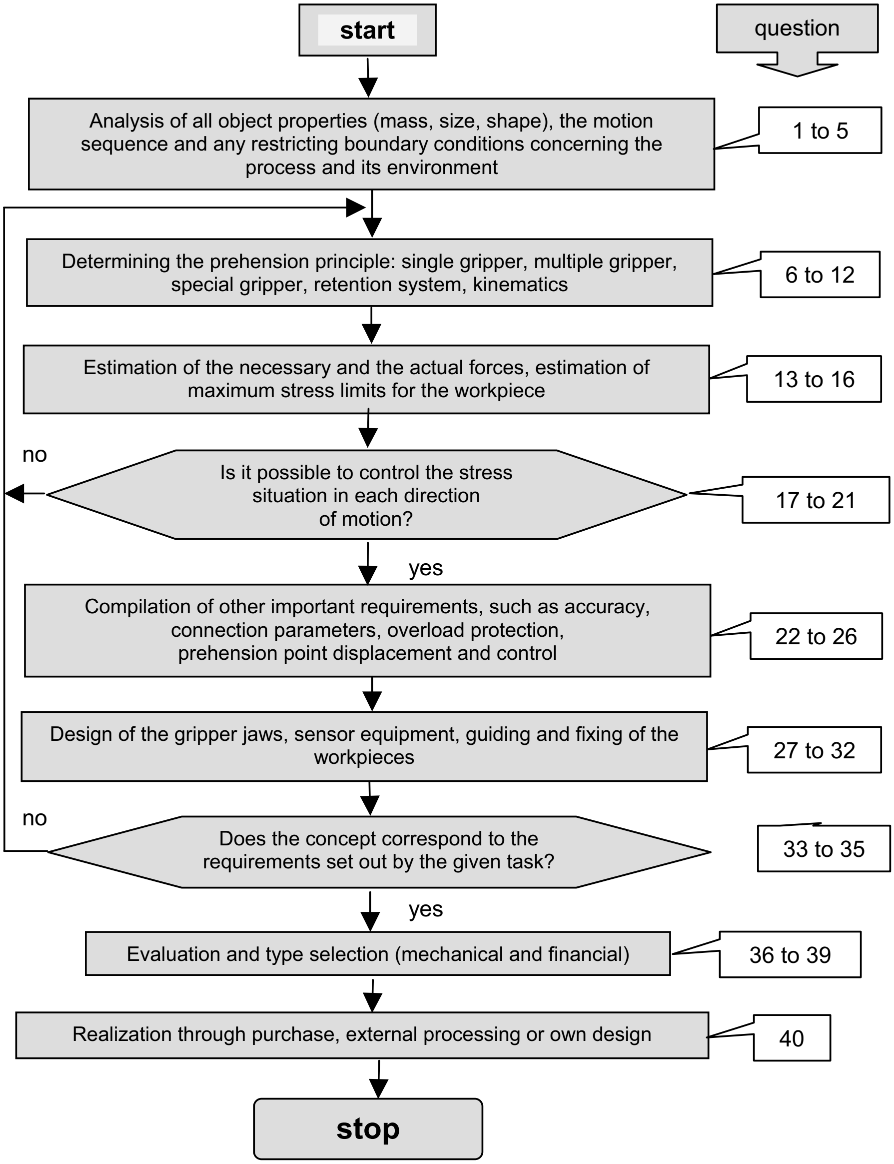


Fig. 2.61: Flowchart guide to aid gripper selection

On the other hand temporal constraints may rule out the use of multifunctional gripper systems (turrets, exchange systems etc.).

The switching times for revolver grippers with a rotational angle of 60° typically lie between 0.1 and 0.5s, which are relatively fast and certainly quicker than the transfer procedure from one robot workcell to another. However, a single robot must carry out all the necessary tasks in sequence making pipelining impossible. As a rule of thumb it makes sense to employ automatic gripper exchange systems if at least five geometrically different component types are to be handled or if the processing time per batch does not exceed two hours.

Distance measurement, positioning, identification, collision avoidance etc., makes sensory integration in almost all modern robotic systems essential (see Chapter 11). Finally, some auxiliary functions should also be mentioned. These include, for example, cooling of the gripper jaws in thermal material (casting, sintering etc.) processing. A flowchart guide to aid gripper selection follows in Figure 2.61. Similar algorithms consist of checklists [1-1] or schemes employing the process of elimination to reach the required goal.

It is possible to formulate some typical questions for each individual step useful in ascertaining the essential properties. Such important questions are:

1. Are the object properties, especially the mass, size, fragility and surface quality, sufficiently known?
2. Is physical access to the object possible?
3. Is the prehension task completely defined with all necessary details? Are the initial and final spatial positions of the object defined?
4. Should the raw and finished part geometries (shape modification as a result of the operation) be accomplished by a single gripper?
5. Are all working conditions (pressure, temperature, object status, cycle time, friction coefficient, mass, etc.) known?
6. Should the object be held by force and/or shape matching?
7. Should one use an impactive or an astrictive principle?
8. Are the prehension surfaces (careful: there may be forbidden surfaces!) given?
9. Will the workpiece be held at, or in the vicinity, of its mass centre of gravity?
10. Does it make a sense to use a gripper exchange system for the handling of several different components?
11. Is it planned to have shape matching in the direction of the largest acceleration component?
12. Does the retention situation in the magazine correspond to the application situation in the machine?
13. Should process forces, for example: joining by pressure, be taken into account?
14. Is it reasonable to consider friction enhancing overlays for the gripper jaws (adhesive coatings, knurled jaws etc.)?
15. Are the gripper and manipulator designed for the largest possible forces and moments? Is the gripper insensitive to impacts and vibration?
16. Will the workpiece bear the exerted surface pressure?
17. Will the gripper sustain emergency switch-off at high velocities?

18. Has a safety factor been taken into account when dimensioning the gripper?
19. Should the prehension force be reduced in order to protect the workpiece?
20. Is it necessary to secure the prehension force (mechanical retention)?
21. Does it make a sense to include collision and overload protection?
22. Does the achievable gripper accuracy satisfy the requirements?
23. Does the potentially interfering contour of the opened gripper pose a collision danger with the surroundings?
24. What effects on object centration (measurement and alignment) can be expected from the gripper?
25. Which activation approaches, e.g. electrical or pneumatic, can be recommended to the user?
26. Is sensory prehension verification necessary (check of object presence)?
27. Are the gripper fingers as short as possible?
28. Should the finger position be controlled by sensors?
29. Should it be recommended to switch in some joining mechanisms and/or force sensors, during assembling operations?
30. Is it planned to have several gripper jaw applications (consider rapid replacement)?
31. Will it be necessary to insert adaptor flanges for mounting? Are practicable mechanical, fluidic, and electrical interfaces available?
32. Should the gripper jaws compensate for non-parallel object surfaces?
33. Is the achievable processing time (gripping, moving, releasing) acceptable? Do the opening and closing times satisfy the requirements? Are these times increased when the gripper fingers or jaws are installed?
34. What is the likely mean time between failures?
35. Are any upper limits for maximum load exceeded?
36. Is it possible to use a standard gripper or is it necessary to employ a special solution?
37. What is an acceptable delivery time?
38. Which warranty regulations are applicable (often dependant on national law)?
39. Should it be planned to include auxiliary equipment (pusher, gripper magazine, etc.)?
40. Is the gripper selection complete or is expert advice necessary?

In the event that a completely new gripper design is necessary, established procedures known from design theory may be utilised [2–25]. These are basically:

1. Clarification and specification of the task → problem analysis, formulating the requirements (requirement specifications), abstract procedure for structuring of the problem.
2. Identification of functions and their structures → creativity techniques, intuitive and discursive methods of solution identification, establishing procedures and function structures.
3. Search for solution methods and structures → options, selection criteria and weightings.
4. Breaking down into realizable integral parts → modularization of the structure.

3
Impactive Mechanical Grippers

The object retention force provided by mechanical grippers is based on the physical effects of classical (*Newtonian*) mechanics, mainly associated with mass points and forces, and requiring more or less extensive mechanisms. These are the most frequently used grippers with a great variety of technical realizations. Normally they posses between two and four fingers which, in most cases, move synchronously. Adequate design may also additionally make them capable of object centring whereas in the case of astrictive grippers, additional hardware may be necessary to facilitate object positioning. As a rule, Impactive grippers affect the mating between workpiece and jaw surfaces. Universal multi-finger grippers having up to five jointed fingers, often known as dextrous hands, are still mainly research ideas and are presently of little industrial relevance.

The often complicated designs of impactive mechanical grippers are compensated by their operational reliability, ability to provide adequate (and often adjustable) force, shape and/or force matched prehension as well as their good adaptability with respect to handling operations.

3.1
Gripper Drives

Finger motion can be realized by a number of possible prime movers. This is accomplished by converting some form of energy into mechanical energy which corresponds to the required form of motion [3-1]. The drive chain contains a motor, gear, brake or attenuating elements with possibly travel and angle measurement systems. Figure 3.1 shows a general block scheme of such a drive structure.

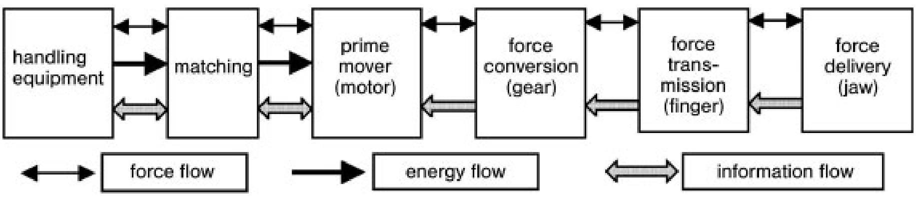


Fig. 3.1: General structure of a gripper drive chain

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

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The gear is a motion converter transforming the drive parameter x into the drive parameter y. One distinguishes between transmission and guidance gears.

Guidance gears guide points, planes or bodies of some mechanism with actuated links along a predefined path in two or three spatial dimensions.

Transmission gears are motion, and hence force converters. In most cases they transmit rotational energy from an input to an output axle (usually with a rotational speed reduction).

The following gear types are most widely used as kinematic systems or "gripper gears" for impactive grippers:

- Jointed mechanisms (lever gear)
- Screw gear
- Wedge gear
- Cam gear
- Wheel gear, also rack wheel, and rack and pinion gear
- Pull and pressurizing medium gear

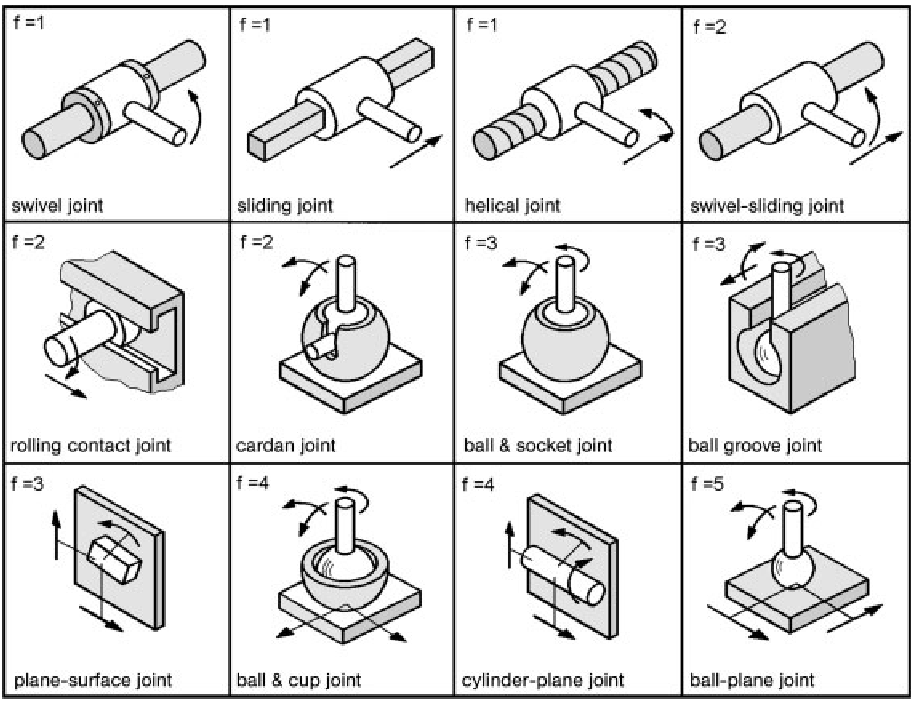


Fig. 3.2: Joint designs with their designation and degrees of mobility

Lever gears consist of joints and links. A joint consists of two elements, one per link. Joints can possess different forms of mobility, e.g. rotational, translational, spherical, or helical motion. For example, ball-joints exhibit three degrees of freedom ($f k = 3$) because their output link is pivotable in three axes. Typical gear joints have $f k = 1$. Figure 3.2 illustrates several joint designs.

All mechanical joints have a basic common problem. Their principle of operation demands a degree of play between their elements in order to allow free movement. However, the greater the play the poorer the mechanical accuracy. This situation can also be exacerbated depending on additional mechanical stresses.

Lever gears are often used in combination with other gears. Figure 3.3 shows some examples of gripper drives.

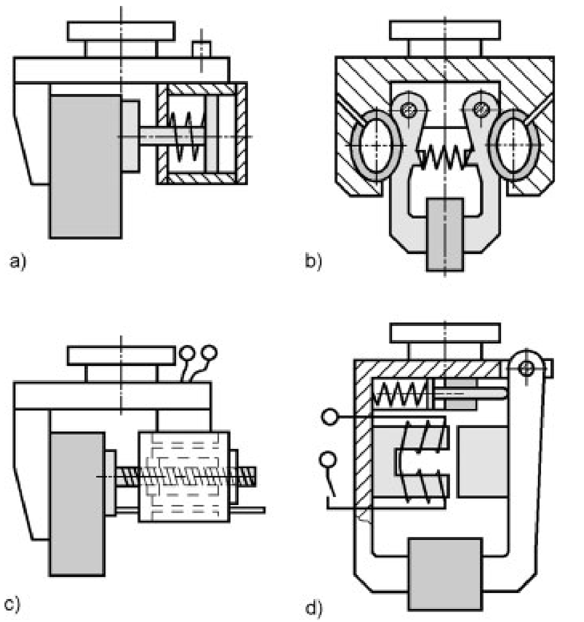


Fig. 3.3: Examples of gripper drives
a) pneumatic cylinder
b) membrane drive
c) electromechanical drive with a rotating screw nut and guiding (skew preventing) rod
d) electromagnetic drive, opened by spring force

If only one finger is moved and the second is fixed then no alignment of the object in the gripper centre is possible. Additional mechanical hardware would be necessary to facilitate alignment in the centre of the gripper jaw, e.g. measurement of the actual deviation of the object from the gripper TCP.

Every drive system is characterized by some specific properties. Most important however, is that the gripper design and properties correspond to the forces acting (Fig. 3.4). Consequently, for most impactive grippers, the following electrical drives are applicable:

- **Stepping motors**
  Application in low-cost proportional systems instead of pneumatic drives.

- **Servo motors (synchronous motors)**
  Used for demanding applications with sensitive force and position regulation; applicable also for simultaneous measurements.

- **Linear motors**
  Applicable to proportional operation at high speeds, i.e. for extremely fast motion of the gripper jaws. In most cases these motors exhibit more limitations than advantages.

- **Piezoelectric drives**
  Applicable for extremely light objects and high speed handling. Their reliability and lifetime is very long but the achievable stroke is somewhat limited.

For electrically driven grippers intended for use in the USA it should be noted that the norms for safety and power supply are quite different to those in Europe. For fire protection reasons the cables and the other materials should be flame resistant. Each US state has its own systems and the voltages are not standard as in Europe. However, since most electrically driven grippers are controlled via industrial standard 24 volt DC supplies (PLC compatibility) the corresponding norms in USA and Europe are comparable in this respect.

Some examples of drives will now be discussed. In most cases several alternative solutions also exist and the choice is based on the corresponding boundary conditions.

drive system / evaluation criteria	mechanical	pneumatic	hydraulic	magnetic	electric motor
high gripping force	◐	○	●	◐	○
controllability	○	○	◐	●	●
energy transmission	●	◐	○	●	●
insensitivity to dirt	●	◐	●	○	◐
maintanence	●	◐	◐	○	◐
emergency stop behaviour	●	◐	◐	○	○
constructional size	○	○	●	◐	◐
environmental influences	●	◐	○	●	●
costs	●	●	◐	◐	○

Fig. 3.4: Properties of different drives [3-2]
● = advantageous
○ = unfavourable

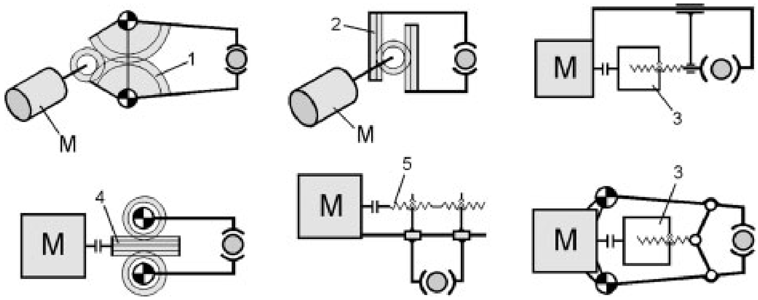


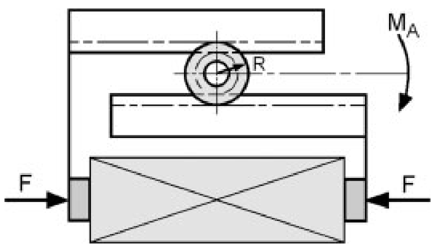
Fig. 3.5: Basic design strategies for grippers driven by electric motors
1 tooth segment, 2 toothed rack and pinion gear, 3 spindle nut, 4 toothed rack,
5 right-left handed threaded spindle, *M* motor

3.1.1 Electromechanical Drives

Most electromechanical drives used in grippers are based on spindle or rack and pinion gears as force converters. Although their portion of the market is not large compared to the other types of drive, as can be seen from Figure 3.5 several different designs are in common use.

Spindle driven gripper jaws normally enjoy a relatively large stroke not normally achievable with other gear types. As a prime mover almost any form of electrically commutated DC servo motor is suitable.

Example: The toothed rack and pinion gear of the small impactive parallel jaw gripper shown in Figure 3.6 is to be driven by an electric motor.



F gripping force
M_A moment (torque)
R pinion wheel radius

Fig. 3.6: Gripper with a toothed rack and pinion mechanism

The prehension force is obtained from the relation

$$F = \frac{M_A}{2 \cdot R} \tag{3.1}$$

For most rotary actuators such as electric motors, the torque M_A can be assumed to be constant over the complete gripping range. However, when the jaws close the motor stalls. For DC motors this can result in an excess of current resulting in overheating and eventu-

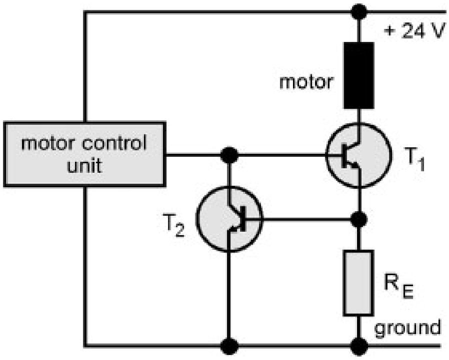


Fig. 3.7: Fold-back current limit for a gripper drive motor

ally burn out. Switching off the motor current completely is unlikely to be a satisfactory solution, especially where a good quality rack and pinion mechanism is used, owing to the likelihood of the object working loose during motion. Fortunately, whilst the object is held between the fingers it is often possible to reduce, or at least limit, the motor stall current by using a fold-back current limiting circuit as shown in Figure 3.7.

Given a simple single transistor motor driver T_1, current limiting is achieved by inserting a second transistor T_2 in the base-emitter circuit of T_1. The voltage between base and emitter of T_2 cannot exceed 0.7 volts (or thereabouts for a silicon bipolar transistor).

According to *Ohm's* law one has:

$$U_{BE2} = I_{E1} \cdot R_E = 0.7\ V$$

Hence, the resistance for the required current limit is given by

$$R_E = \frac{0.7}{I_{E1}}$$

Consequently, as current flowing through the motor (and R_E) rises, so does the base emitter voltage of T_1. As this approaches 0.7 volts, transistor T_1 starts to conduct pulling down the base of T_2 and eventually switching it off should the current through R_E be large enough to turn T_1 completely on.

A mechanical alternative is to include a gear system which cannot be back driven between the motor and pinion so that the motor can be switched off rather than run in "stall mode". Due to the additional gear translation the price is of course reduced speed. Strong acceleration forces in the starting and stopping phases of the gripper motor can be reduced by appropriate control or by the introduction of an additional damping element between the motor and the gear.

The following computational procedure (referring to the two examples in Figure 3.8) is recommended for the actuation of grasping organs by electric motors.

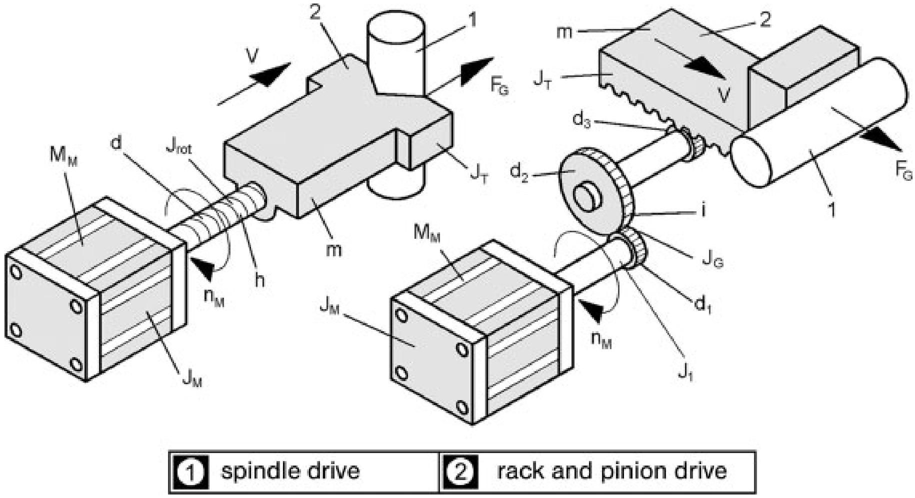


Fig. 3.8: Examples of gripper jaw drives using electric motors

The notations used in Figure 3.8 have the following meaning:

n_M motor speed [revolutions min^{-1}]
h thread pitch [mm]
v speed [m/min]
m mass [kg]
M_L load moment [Nm]
J_L moment of inertia of translationally moved mass [kg m^2]
J_{rot} moment of inertia of rotationally moved mass [kg m^2]
F_G gripping force [N]
M_M motor moment [Nm]
i transmission ratio ($i = d_2/d_1 = n_M/n_w$)
d diameter [mm]
η spindle efficiency

{1} spindle drive **{2} rack and pinion drive**

- Calculation of the number of motor revolutions n_M dependent on the required closing speed v

$$\{1\}\quad n_M = \frac{1000 \cdot v}{h} \tag{3.2}$$

$$\{2\}\quad n_M = \frac{1000 \cdot v \cdot i}{\pi \cdot d_3} \tag{3.3}$$

- Determination of the load moment M_L

$$\{1\}\quad M_L = \frac{F_G \cdot h}{2 \cdot \pi \cdot \eta \cdot 1000} \tag{3.4}$$

$$\{2\}\quad M_L = \frac{F_G \cdot d_3}{2 \cdot 1000 \cdot i \cdot \eta} \tag{3.5}$$

- Determination of the moment of inertia J_T of the translated masses

$$\{1\}\ J_T = m\left(\frac{h}{2 \cdot 1000 \cdot \pi}\right)^2 \qquad (3.6) \qquad\qquad \{2\}\ J_T = m\left(\frac{d_3}{2 \cdot 1000}\right)^2 \qquad (3.7)$$

- Determination of the moment of inertia J_R of the rotationally moved masses

$$\{1\}\ J_R = \frac{m_{rot} \cdot d^2}{8 \cdot 10^6} \qquad (3.8) \qquad\qquad \{2\}\ J_R = \sum_{i=1}^{i=5} \frac{m_{roti} \cdot d_i^2}{8 \cdot 10^6} \qquad (3.9)$$

Cylindrical bodies are assumed in these calculations. d_i denote the wheel diameters d_1, d_2, d_3 as well as the shaft diameter. The same holds for the masses m_{roti}. The mass can be calculated from $m = p \cdot V$ where

ϱ = 7.85 kg/dm^3 for steel
ϱ = 2.71 kg/dm^3 for aluminium
ϱ density in kg/dm^3
V volume of the i-th body in dm^3

- Summing the moments of inertia yields J_{ges}

$$\{1\}\ J_{ges} = J_M + J_T + J_R \qquad (3.10)$$

$$\{2\}\ J_{ges} = J_M + J_1 + \frac{J_2 + J_G + J_T}{i^2} \qquad (3.11)$$

The motor moment of inertia can be taken from the manufacturers specifications. In the same way J_G for rack and pinion drives can also be found.

- Evaluation of the acceleration torque M_a

$$\{1\} \text{ and } \{2\} \qquad M_a = \frac{J_{ges} \cdot n_M}{9.55 \cdot t_a \cdot \eta} \qquad (3.12)$$

t_a acceleration time in s

- The moment of friction M_R is obtained from

$$\{1\}\ M_R = \frac{9.81 \cdot m \cdot \mu \cdot h}{2 \cdot \pi \cdot \eta \cdot 1000} \qquad (3.13) \qquad\qquad \{2\}\ M_R = \frac{9.81 \cdot m \cdot \mu \cdot d_3}{2 \cdot 1000 \cdot i \cdot \eta} \qquad (3.14)$$

Typical coefficients of friction applicable to use in the above equations are:

adhesive friction $\mu = 0.12$ to 0.15
mixed friction $\mu = 0.01$ to 0.1
sliding friction $\mu = 0.001$ to 0.015

- The required angular momentum M_{imp} is then obtained from

$$M_{imp} = M_L + M_a + M_R \tag{3.15}$$

- The required constant torque is given by

$$M_d = M_L + M_R \tag{3.16}$$

- Now the motor must be chosen according to its torque and speed (min^{-1}). It may also be necessary to retroactively correct some original data, as e.g. the acceleration time.

$$P_M = \frac{M_N \cdot n_M}{9.56} \tag{3.17}$$

P_M motor power [W]
M_N motor moment [Nm]

- Finally, the controller must be selected according to current and voltage requirements before evaluating the actual thermal load on the motor.

Naturally there are many other kinematic arrangements for grippers driven by electric motors. Some of them have already been illustrated in Figure 3.5. The determination of the motor size should be done following a similar procedure whereas the calculation of the mass moments of inertia must be repeated in each individual case.

Electromagnets are rarely used as motion generators. Two concepts for the driving of gripper fingers in impactive grippers are presented in Figure 3.9 [3-3]. In the first case the two end positions of the moving finger are secured by spring forces. In the second example this role is fulfilled by permanent magnets. The disadvantages in this case are related to the abrupt (non-linear) behaviour of the prehension process and inertial moments of the electromagnets.

One popular and space saving gripper design is shown in Figure 3.10. It is based on a wedged clamp gear. Any linear motion produced by a spindle or the pneumatic piston is transformed by the shape matched wedge into transverse motion of the jaws.

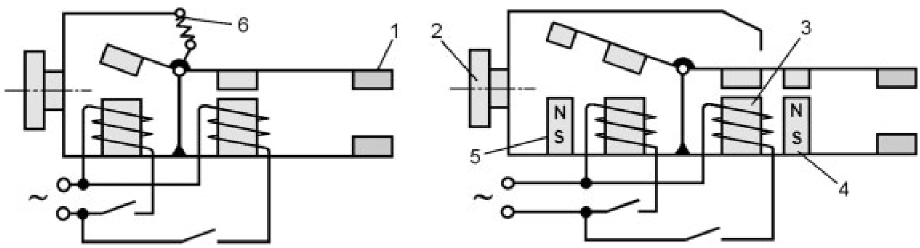
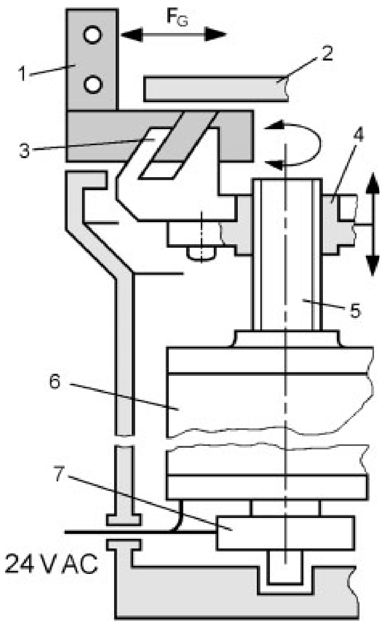


Fig. 3.9: Magnetic drive for impactive grippers
1 gripper finger, 2 gripper flange, 3 electromagnet, 4 permanent magnet providing holding force, 5 permanent-magnet for holding the gripper open, 6 return spring



1 jaw
2 guideway
3 wedged clamp system
4 spindle nut
5 spindle
6 servo motor
7 resolver

F_G prehension force

Fig. 3.10: Three finger gripper driven by an electric motor through a wedge clamp gear

3.1.2 Pneumatic Drives

The most frequently used impactive grippers are pneumatically driven. Actuation is realized either by pneumatic cylinders integrated within the gripper housing or by externally mounted cylinders. Such prime movers are robust and resistant to overload. Both single-acting cylinders with spring return or double-acting devices are available. The piston force F can be obtained from the following equation:

$$F = p_e \cdot A \cdot \eta \tag{3.18}$$

p_e working pressure ($p_e = p_{abs} - p_{amb}$; $p_{amb} \approx 1$ bar)
A cylinder internal cross sectional surface area
η efficiency

p_{amb} is often taken as 1.1 or 1.2 Bar as a safety margin to allow for changes in atmospheric pressure.

Typical values for the efficiency (dependant on air leakage, friction etc.) are:
- for high quality single-acting and double-acting cylinders $\eta > 0.9$
- for cheaper double-acting cylinders with lip seals $\eta = 0.7$ to 0.9

Air consumption for double-acting cylinders is obtained from the following equation:

$$Q_{Hub} = \frac{2 \cdot d^2 \cdot \pi \cdot s \cdot p_{abs} \cdot n}{p_{amb}} \tag{3.19}$$

Q_{hub} cubic capacity [Litre/min]
d piston diameter [m]
s travel [m]
p_{abs} absolute pressure [bar] (pressure relative to absolute vacuum)
p_{amb} atmospheric pressure [bar]
n number of switching cycles [min^{-1}]

The factor 2 should be omitted in the case of single-acting cylinders.
As previously mentioned, in most cases a factor of about 10 to 20% is also allowed for air leakages etc.

Example:
Given: $d = 35$ mm, $s = 80$ mm, $p_e = 6$ bar ($p_{abs} = 7$ bar), $n = 50$ min^{-1}
Determine the air consumption Q_{Hub}

$$Q_{Hub} = \frac{2 \cdot d^2 \cdot \pi \cdot s \cdot p_{abs} \cdot n}{4 \cdot p_{amb}} = \frac{2 \cdot 0{,}35^2\ \mathrm{dm}^2 \cdot \pi \cdot 0{,}8\ \mathrm{dm} \cdot 7\ \mathrm{bar} \cdot 50}{4 \cdot 1\ \mathrm{bar} \cdot \mathrm{min}} = 54\ \frac{l}{\mathrm{min}}$$

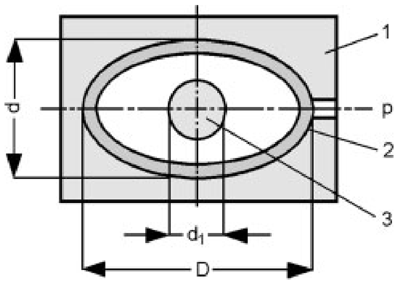
Adding a factor for leakage losses etc. of approximately 10% gives a total air consumption of about 60 l/min.

As pneumatic cylinders tend to be used in "bang-bang" operations – full movement in one direction or the other – lifetime of the device may be reduced if the piston is constantly being driven against the end stops. Fortunately to prevent this, pneumatic cylinders are available which employ integrated shock absorbers with adjustable choke valves. These are however more expensive than simple cylinders and are consequently not always utilised by gripper manufacturers. One almost as good alternative is to fit non-return choke valves in the pneumatic cylinder air inlet (and/or in the outlet). These limit the speed of jaw movements and when carefully adjusted can extend gripper lifetimes without seriously compromising speed of operation (see Fig. 2.42).

For the optimal utilization of available installation space within the gripper housing, oval pistons are sometimes used owing to their larger surface area. In accordance with Figure 3.11, the piston force on the oval ring-surface or the oval surface is given by:

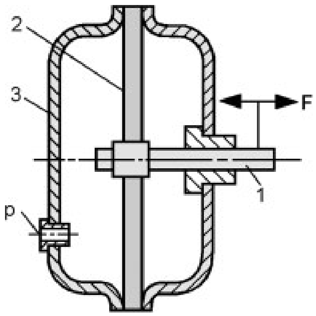
ring surface $A = \frac{\pi}{4}(D \cdot d - d_i^2)$ or **oval surface** $A = \frac{\pi}{4} D \cdot d$ (3.20)

piston force $F = p \cdot A$ (3.21)



1 gripper housing
2 piston gasket
3 piston rod
ϱ compressed air inlet

Fig. 3.11: Oval piston drive



1 piston rod
2 membrane
3 housing

ϱ compressed air
F force

Fig. 3.12: Membrane drive

When membrane cylinders are used as gripper drives (Fig. 3.12) an additional factor λ must be considered in the calculation of the piston force:

$$F = p \cdot A \cdot \lambda \tag{3.22}$$

A piston surface area
λ membrane stiffness factor ($\lambda = 0.3\ldots0.9$)

In addition to membrane and or roll-membrane drives there is another interesting and efficient pneumatic drive, the fluid muscle.

Figure 3.13 shows a gripper for the handling of empty wooden transport palettes. A fluid muscle (*Festo*) is used as a prime mover because it can develop large initial forces and has a relatively small mass. It has typically a nominal length of 1100 mm which shortens by 120 mm (its stroke) while developing a force of 700 N when compressed air is supplied [3-4]. The fluid muscle diameter is only 20 mm. Because it is hermetically sealed, this drive is absolutely insensitive to dirt and dust. Moreover, its motion is free of any static friction (stick-slip effects). As in the previously mentioned usage of cylinders with choke valves, it is possible to achieve a soft arrival by the usual means of pneumatic damping. Round guideways for the grasping organs are arranged on the left and right sides along the

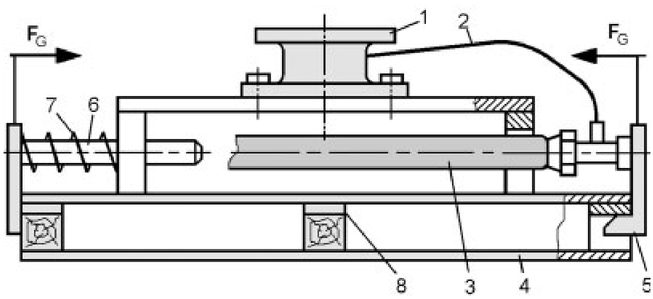
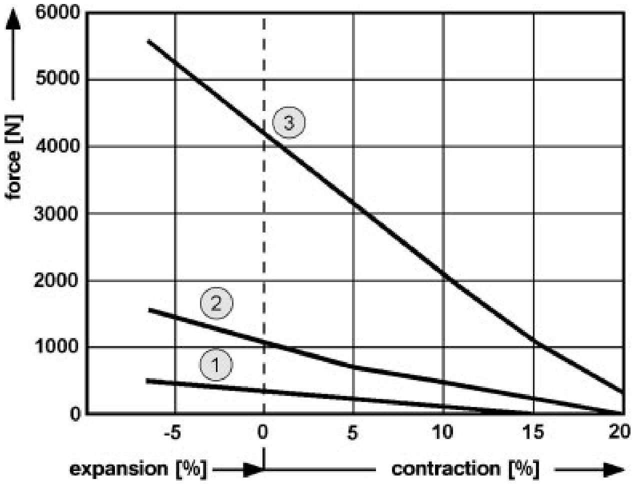


Fig. 3.13: Empty palette gripper (*Schmalz*)
1 flange, 2 compressed air line, 3 fluid muscle, 4 transport palette, 5 fixing plate, 6 straight line guide, 7 return spring, 8 transverse beam, F_G prehension force

muscle. In contrast to pneumatic cylinders, fluid muscles cannot be used for guiding operations. They are purely traction force actuators with digressive characteristic force to stroke dependence. Consequently, all moving components must be appropriately guided.

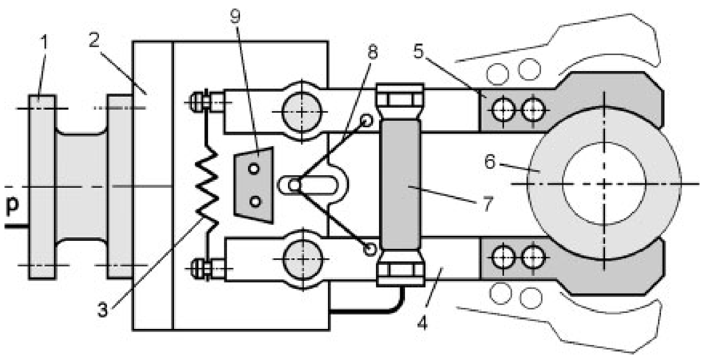
The curves for maximum force development of the muscle at 6 bar are shown in Figure 3.14. The pre-elongation should not exceed 3% of the nominal length. The design can be carried out graphically using force-contraction diagrams or somewhat more accurately using a computer program, e.g. "*Muscle SIM*", which can be downloaded from the internet (www.festo.com/download).



1 diameter 10 mm
2 diameter 20 mm
3 diameter 40 mm

Fig. 3.14: Force development in a fluid muscle

Figure 3.15 shows yet another configuration employing a *fluid muscle,* in this case to move the jaws. The gripper is mechanically simple and lighter than many motor driven grippers whilst providing considerable retention force. The gripper fingers are mechanically coupled in order to synchronize jaw motion. If the fluid muscle is mounted close



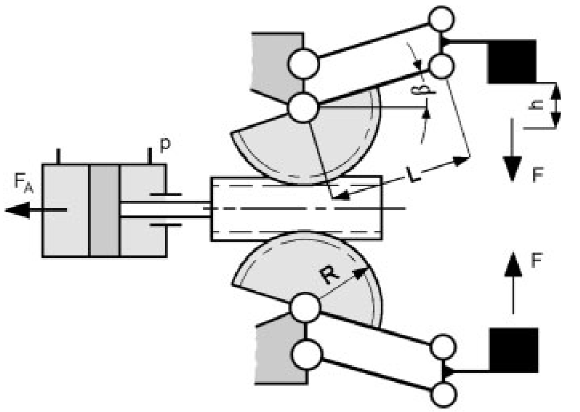
1 flange
2 gripper housing
3 tension spring
4 gripper finger
5 gripper jaw
6 workpiece
7 fluid muscle
8 rod for motion synchronization
9 finger stop

ϱ compressed air

Fig. 3.15: Simple angle gripper

enough to the finger pivot points, a short muscle is sufficient for the clamping motion. The efficiency of this gripper is high because frictional resistance must be overcome only in the round guideways. Opening angles approaching 90° for every finger are, however, impossible to achieve with this design. For such purposes, a different kinematic configuration must be selected.

Example: A two jaw gripper is to be used for the handling of workpieces of mass 60 kg. The maximum gripper acceleration should not exceed $a = 5\ \text{m/s}^2$. The gripper object is moved in both vertical and horizontal directions whereas the direction of acceleration can coincide with the direction of the gravitational force. The workpiece width can vary between $b_1 = 60$ mm and $b_2 = 200$ mm. A 125 bar (= 12.5 MPa) hydraulic supply is available. Determine the necessary diameter d of the hydraulic cylinder.



F gripping force
h additional jaw travel
R gear segment radius
F_A piston drive force
ϱ pressure

Fig. 3.16: Principle of the two-jaw gripper ($L = 150$ mm)

The gripper kinematics shown in Figure 3.16 is preferable because it allows for a larger jaw travel. Friction forces alone must hold the workpiece between the gripper jaws. The following friction coefficients can be used (see Chapter 2 for more detailed data):

- Workpieces with flat surface, slightly oiled $\mu = 0.1$
- Gripper jaws with sharply knurled surfaces $\mu = 0.3$ to 0.4
- Gripper jaws with anti-slip coating (metal-rubber) $\mu = 0.5$ to 0.7

For the given example a friction coefficient of $\mu = 0.15$ and a safety factor of $S = 1.5$ will be adopted.

Estimation of the gripping force:

$$F = \frac{m\,(g + a) \cdot S}{2 \cdot \mu} = \frac{60\,(10 + 5) \cdot 1.5}{2 \cdot 0.15} = 4500\ \text{N} \tag{3.23}$$

The driving force F_A required to produce such a griping force can be calculated from:

$$F_A = F \cdot i \tag{3.24}$$

The transmission ratio i for the force conversion is obtained from (3.25)

$$i = \frac{2 \cdot L \cdot \cos\beta}{R} \tag{3.25}$$

The angle β takes into account the maximum jaw displacement s, resulting from the variable prehension range. Moreover, the jaws must open wider by an amount h so that the opened gripper can be moved sideways to the prehension position. A value of $h = 20$ mm can be added for play.

This gives the following jaw displacement s

$$s = \frac{(b_1 - b_2)}{2} + h = \frac{200 - 60}{2} + 20 = 90\,\text{mm} \tag{3.26}$$

Furthermore, one has

$$\sin\beta = \frac{s}{L} = \frac{90}{150} = 0.6 \qquad \text{and hence } \beta = 36°\ 50'$$

In order to determine the radius of the cog wheel R it is necessary to know the tooth pitch m. Assuming $m = 5$ mm and the number of teeth $z = 17$, one obtains

$$R = \frac{m \cdot z}{2} = \frac{5 \cdot 17}{2} = 42.5\,\text{mm, and for the transmission ratio} \tag{3.27}$$

$$i = \frac{2 \cdot 150}{42.5} \cdot 0.8 = 5.65$$

It is now possible to evaluate the driving force F_A:

$$F_A = 4500 \cdot 5{,}65 = 25\,425\ \text{N}$$

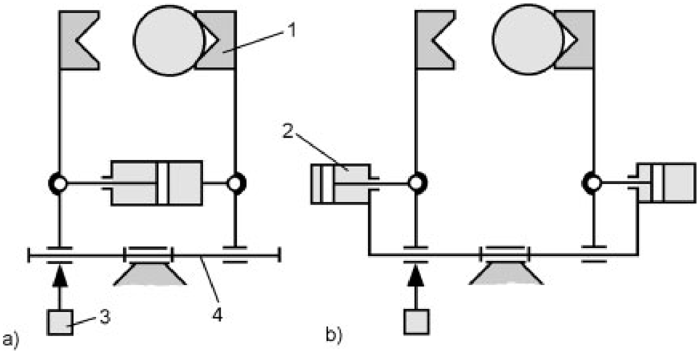
This force must be produced at the piston rod side of the cylinder. Given a piston rod diameter of $d_s = 20$ mm. Then (3.28) gives the piston internal diameter d

$$d = \sqrt{\frac{F_A \cdot 4}{p \cdot \pi} + d_s^2} = \sqrt{\frac{25\,425 \cdot 4}{12.5 \cdot 3.14} + 20^2} = 54.6\,\text{mm} \tag{3.28}$$

A hydraulic cylinder with a piston diameter of 56 mm or greater should be chosen.

If the workpiece position and/or orientation are not precisely known it may be necessary to equip the gripper with compensating elements.

Conformal, or self-adjusting, grippers can adapt themselves to the position of the prehended object by deliberately introducing a controlled degree of play. This adaptation can be active or passive (Fig. 3.17). The position of the object may be inaccurate and random. In the case of active adaptation each finger has its own drive and may be guided by sensors.

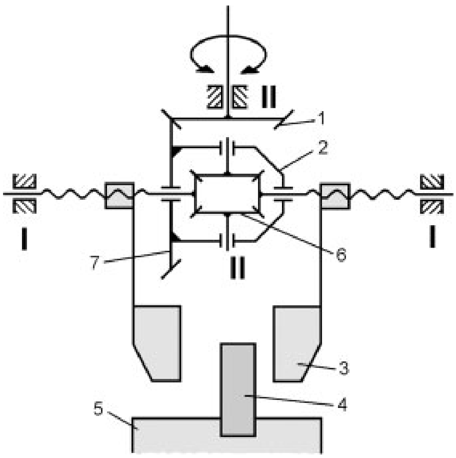


1 gripper jaw
2 drive
3 toggle
4 finger guideway

Fig: 3.17: Principle of grippers with conformal grasp
a) passive compensation, b) active compensation

In the case of passive conformal grippers the fingers are centred on the object and have a common drive and there are no elastic elements for compliance. As in the previous case the objects are handled sequentially. A mechanical togglecan be used to lock the final finger positions.

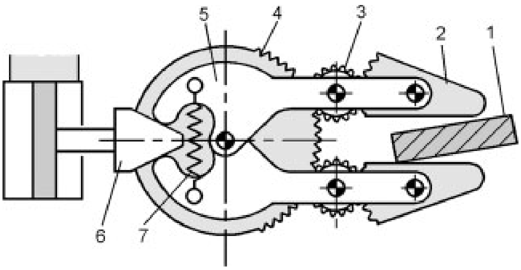
The gripper depicted in Figure 3.18 is equipped with a compensating gear which allows for uniform distribution of the drive power between the two fingers. The mode of operation is similar to the differential gear of a car. This gripper offers the ability to prehend parts which are positioned offset from the gripper centre and unable to move. The differential control allows the gripper jaws to automatically adapt themselves to the object. There is no over determination with unacceptable forces acting on the gripper or the delivery equipment. If no compensation is required, the bevel gear wheel with the compensation star rotates around the axis I – I. At the same time the compensating pinions do not rotate around the axis II – II, they effectively act as a fixed coupling. When a gripper jaw makes contact with the object compensation is required, i.e. the other threaded spindle



1 drive pinion
2 compensation star
3 gripper jaw
4 gripped object
5 provision magazine
6 compensation pinions
7 bevel gear wheel

Fig 3.18: Gripper with adaptation to the workpiece position must rotate further. As a result, the compensation wheels rotate not only around the I – I axis but in addition around the II – II axis. The technical efforts required to design such gear systems are obviously considerable. A more elegant solution is, of course, to install simple and flexible magazine delivery equipment.

The self-adaptation to the workpiece orientation can also be realized by a different type of compensation wheel , as illustrated in Figure 3.19. The gripper jaws always remain parallel to each other, however, as a pair, they can adapt themselves to the object by changing their alignment angle.



1 workpiece
2 gripper jaw with gear segment
3 intermediate wheel
4 compensation wheel
5 pivoting finger
6 cam slide

Fig 3.19: Gripper with adaptation to the workpiece orientation [3-5]

Setting one of the gripper jaws at an angle leads to adjustment of the compensation wheel. This wheel pivots in turn the other gripper jaw by the same angle. Consequently, it is necessary to consider the force flow in both the gripper and the industrial robot. The force flow should be considered as a closed loop both at the large (e.g. handling equipment guidance gear) and the small (e.g. mechanical impactive gripper) scale. This is schematically shown in Figure 3.20. The design engineer must determine the correct cross sections, strengths, and materials for all parts included within the force circuit. The same holds for the bearings, loads and any possible play.

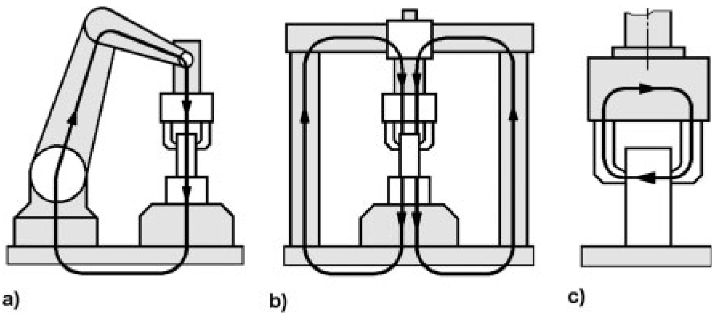


Fig. 3.20: Force flow diagram for an industrial robot and a gripper
a) force circuit in a free arm robot
b) robotic palletizer
c) force circuit in an impactive gripper

3.1.3 Electrostrictive and Piezoelectric Actuation

Piezoelectric and electrostrictive crystals of one sort or another have been around for approximately a century. Piezoelectric elements can be used either as sensors, where an applied force generates a voltage, or as actuators, where an applied electric field causes the element to expand along one axis and contract along the orthogonal axes. Electrostriction on the other hand has no inverse and is consequently confined to use in actuators. Figure 3.21 shows a comparison of electrostrictive and piezoelectric effects. Note that electrostriction is a second order effect making the direction of actuator movement independent of electric field polarity.

Both electrostrictive and piezo-electric crystals are basically capacitive elements. This means that current only flows during the charging process (while the actuator is providing motion) and so long as leakage currents can be kept small, force is maintained at the end of the stroke without the need to supply additional energy. This is in complete contrast to electromagnetically driven devices where energy must continue to be supplied if the *full* actuator force is to be constantly maintained.

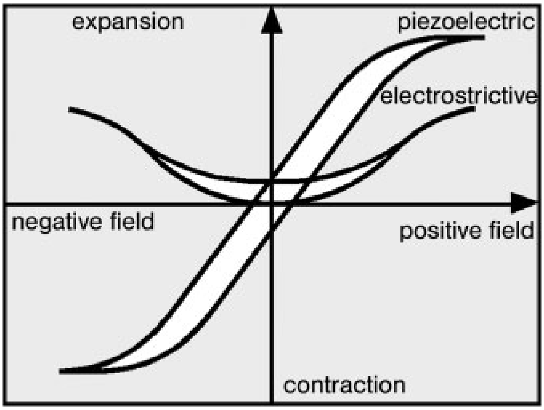


Fig 3.21: Piezoelectric and electrostrictive characteristics for an applied electric field

Electrostrictive elements enjoy lower hysteresis and can produce larger forces than piezoelectric devices of comparable size [3-6]. This makes them ideal candidates for precision actuators in optical positioning systems but their limited stroke, temperature dependence and higher expense makes them less desirable for simple, light load, movement applications. As with most practical engineering designs there is always a trade-off between the available force and the length of the stroke. Single piezoelectric actuator elements can provide many Newtons force but are capable of strains of only a few percent, which translates into fractions of a millimetre for a 1 cm long rod.

Mechanical amplifiers of the type shown in Figure 3.22 are effectively double lever mechanisms which can be used to increase the stroke in a similar way to the mechanical gear systems previously described. A piezoelectric actuator pulls (or pushes) against a bar which is linked to the gripper jaw levers at both sides by two thin beams. The beams are

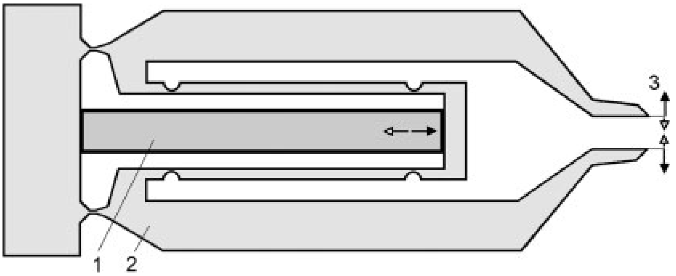


Fig 3.22: Piezoelectric actuator with mechanical amplifier

connected at both ends by flexible hinges which allows them to bow under force from the actuator. Movement is then amplified by the lever effect causing the gripper jaws to close (or open).

This design also enjoys the economy of a single piezoelectric or electrostrictive actuator which provides a linear force in a direction perpendicular to the movement of the jaws. The movement of the actuator causes a flexing of the mechanical amplifier providing a jaw displacement of typically between one quarter and two mm. The resulting force however is reduced, often to less than one Newton, and the characteristic becomes somewhat non-linear towards the end of the movement range.

Many similar designs exist though an interesting variation on this theme is the version developed by the University of Ilmenau's Microsystems department [3-7], where the actuator is placed at right angles to that shown in Figure 3.22 in order to provide a force acting directly against the outer lever bars. The addition of two extra mechanical members provides a switch between hinges of differing flexibility thus facilitating variable gearing. This allows for a larger initial movement which is then reduced to provide a greater force at the end of the stroke.

Both electrostrictive and piezoelectric elements may be stacked to provide a longer stroke with the same force but this results in a much larger device and multiplies the price. On the other hand, if two piezoelectric strips are harnessed together back-to-back, then they can be made to function in a way analogous to the well known bimetal strips used in thermostats. Piezoelectric bimorph and trimorph devices are capable of bending to provide several millimetres of stroke at the tip. As most reasonable quality robots can now safely boast a repeatability well within 20 μm, a gripper stroke of only a few millimetres is more than adequate for the handling of products whose size and positioning will always be within a reasonable tolerance.

The Schunk CDG45 shown in Figure 3.23, is a three finger chuck configuration intended for the handling of compact discs and other light weight components. Designed around a single piezoelectric bimorph actuator in “cross-bow” mode, mechanical amplification is achieved through a conical lever mechanism. Needless to say, the end of finger stroke of around 2 millimetres does not provide the same magnitude of force as might be expected form a similar sized pneumatic gripper, though both force and finger position are proportionally controllable within their working ranges.

Though the gripper is capable of holding about a kilogram under static conditions, actual force developed at the finger tips is under 15 Newton. For its intended applications –

Fig 3.23: Piezoelectric driven gripper for CD handling

internal prehension of CDs, small plastic housings and similar light components – the available gripping force is more than adequate. Full opening and closing times are both around 50 milliseconds.

One real advantage of this kind of gripper is the extremely low power consumption from an easily generated 200 volt low current supply. The light design also facilitates turret mounting without worries over excess weight. Compared with pneumatic devices the piezoelectric drive is also incredibly quiet. The lack of compressed air, pneumatic lines and lubricants makes this type of gripper suitable for clean room, and possibly for work in vacuum environments.

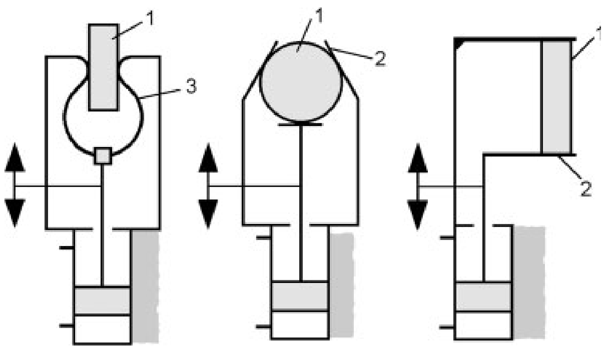
3.2 Design of Impactive Grippers

Most impactive grippers consist of two fingers driven symmetrically with respect to the gripper centre axis. This can be referred to as stereomechanical prehension. The term "scissors gripper" is used when the gripper fingers move along a curved path with a common centre of rotation. Notations used in the technical literature are, however, not always consistent.

3.2.1 Systematics and Kinematics

In contrast to astrictive holding forces, impactive grippers always rely on mechanical motion which must satisfy two basic requirements:

- The grasping organs must be directed in a well-defined manner, usually matched to the given object.
- The motion of the grasping organs must be coupled directly to energy conversion or drive elements.



1 workpiece
2 gripper jaw
3 flat band spring

Fig. 3.24: Simple grippers with degree of freedom $f\mathrm{k} = 1$ and $f\mathrm{k} = 2$, respectively (left: with solid state joint)

A simple joint with a single degree of freedom $f\mathrm{k} = 1$ (rotation or translation) is sufficient only in very limited cases. Some examples are shown in Figure 3.24.

For such designs, closure is typically achieved along a curved path. This means different degrees of actuator displacement for workpieces with different dimensions and/or existing tolerances (see Fig. 2.30).

In general, owing to the wide choice of available gear systems, there exists a very large diversity in design of impactive grippers in which translational or rotational motion is transformed into jaw motion. Figure 3.25 provides a brief overview.

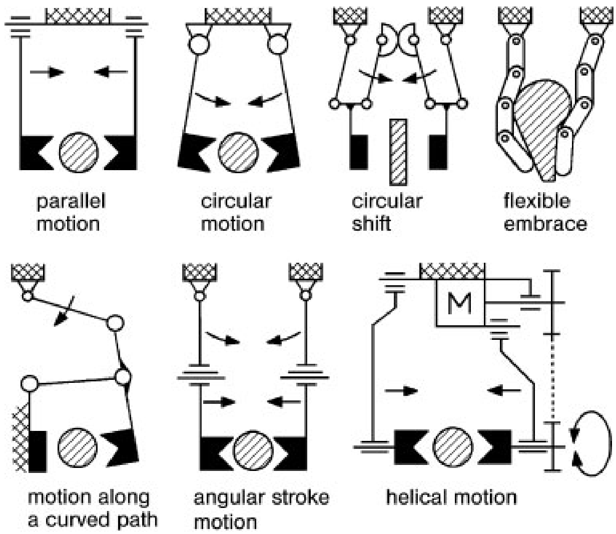


Fig. 3.25: Some typical gripper mechanisms
M motor for jaw rotation

It can be very helpful to be able to understand the function of a gripper gear at a glance. The reduction to a kinematic model makes it possible for the user to see how jaw closure takes place. One distinguishes between:

- parallel motion (whether derived from a curved, circular or linear path),
- rotational motion around a fixed point, and
- general planar motion of the jaws.

The dividing of force for the symmetrical driving of parallel jaws coupled with space saving requirements leads to a defined number of degrees of freedom. To assist in the understanding of such mechanisms, help is at hand in the forms of multi-joint kinematic chains. These are described as follows:

> **Gear degree of freedom**
> The required number of independent actuators in a kinematic chain for defined positive motion of all links.

For planar gripper gears possessing only rotational and shear joints $f\,k_1$ with $f\,k = 1$ the first boundary condition is given by:

$$F = (n - 1) \sum_{i=1}^{g} (3 - f_i) \tag{3.29}$$

n number of gear links
g number of joints i
f_i i-th joint degree of freedom

If sliding/roller and curved joints $f\,k_2$ with $f\,k = 2$ are involved then the 2-nd boundary condition reads

$$F = 3 \cdot (n - 1) - 2 \cdot f_1 - f_2$$

This stereomechanical design is typical for two jaw grippers. Figure 3.26 shows a four joint kinematic chain for a gripper in the opened and closed states.

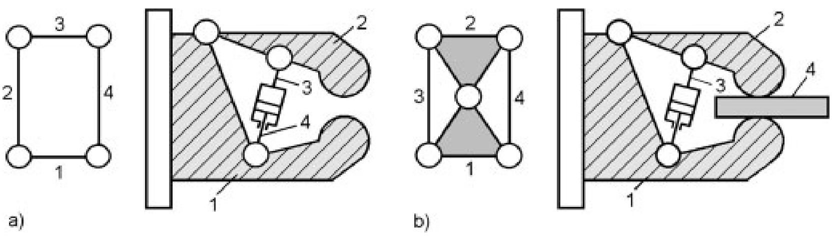


Fig. 3.26: Gripper with a single moving finger (in each case a kinematic chain is shown on the left) a) opened gripper, $F = +1$, b) clamped workpiece, $F = -1$

A corresponding kinematic plan for a range of impactive designs is presented in Figure 3.27. These gripper mechanisms are planar and allow the realization of either planar point manipulation or plane manipulation of the grasping organ. This consideration is independent of the actual transmission gear used (whether lever, curve, knee-lever, wheel, or wedge gears).

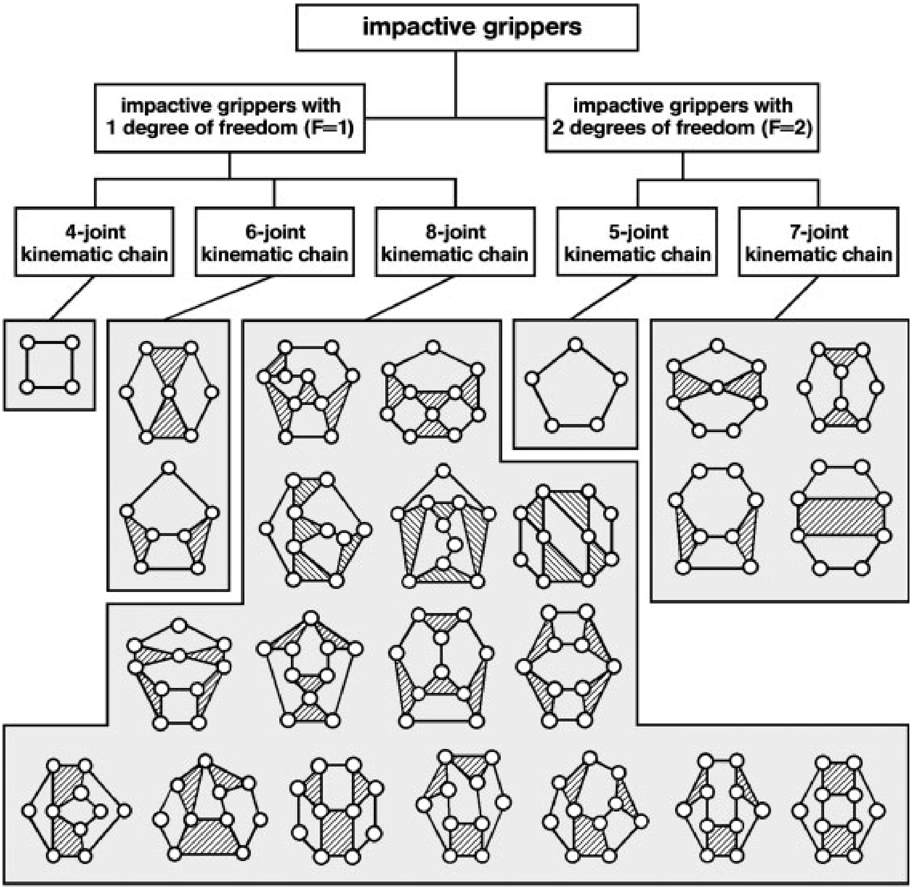


Fig. 3.27: Modelling of the kinematic chains for impactive grippers

Impactive grippers belong to the most widely used end-effector designs. They can be systematically represented by kinematic chains under the rules for gripper technology and they can be easily realized, especially as single drive versions ($F = 1$). A synchronous claw motion can be achieved with double drive ($F = 2$) grippers only by employing additional gear links, e.g. cog wheel sections. This simply consists of positioning a link point for the gripper jaw, which corresponds to one link of the gripper gear, in the plane. The direction of movement of this point can be along a curved or straight path.

Another example is shown in Figure 3.28. In order to apply such a mechanism to the motion of the grasping organ some requirements related to the orientation of the work-piece must first be satisfied and a plane of movement defined.

This concept permits the gripper jaws to seize objects of differing size. One such gear is depicted in Figure 3.29. However, the type of motion chosen leads to displacement of the prehended object mass centre.

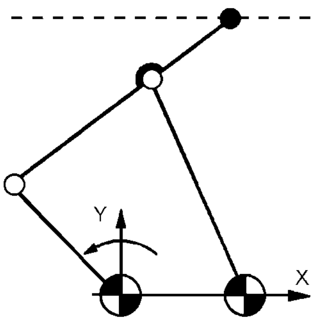


Fig. 3.28: Guidance of a point along a straight line

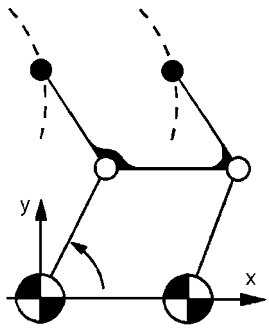


Fig. 3.29: Guidance of a plane (circular-parallel guidance)

Further gears for precise or approximate straight line guidance can be seen in Figure 3.30, represented as kinematic models.

When selecting appropriate gripper mechanics it is also necessary to consider the dependence of the achievable gripping force F_G on the drive travel S_A. This determines the retention reliability. Nevertheless, excess pressure can lead to object surface damage (evaluate the surface pressure).

Using as an example the impactive gripper shown in Figure 3.31, the dependence of the gripping force on the 0-th and 1-st order transmission functions of the underlying gear are clear to see. This dependence can be used to derive special requirements for the kinematic model.

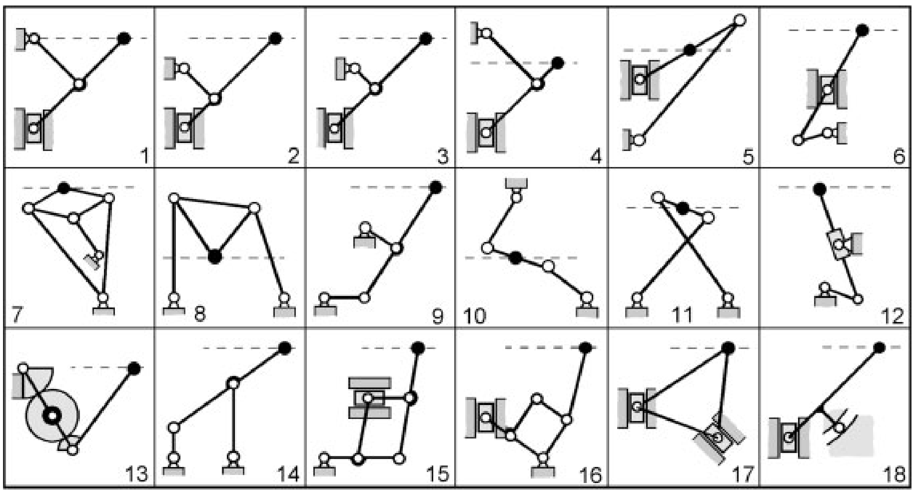


Fig. 3.30: Kinematic schemes for straight line guidance gear
1 Isosceles centred crank, 2 centred crank, 3 general crank, 4–6 central shear cranks, 7 Inverse *Peacellier*, 8 *Roberts* guidance, 9 *Evans* guidance, 10 *Watt* guidance, 11 *Chebishev* guidance, 12 conchoidal guidance, 13 jointed arm, 14 lemniscate guidance, 15 pantograph, 16 plagiograph, 17 double slide, 18 curve lead guidance

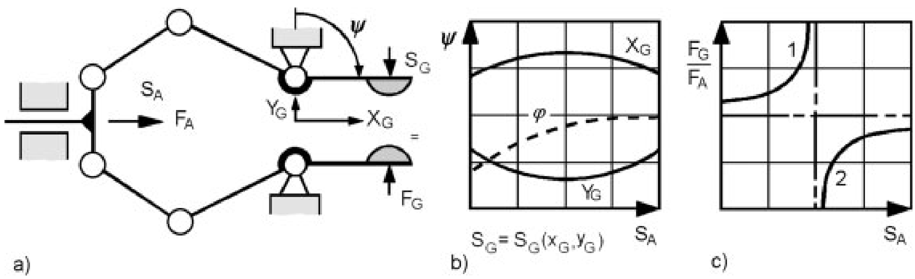


Fig. 3.31: Prehension force dependence for an impactive gripper
a) kinematic model, b) 0-th order transfer function, c) prehension force dependence,
1, 2: motion regions, F_A : constant, X_G and Y_G : object axes, ϕ: drive angle, ψ: output angle

The jaw travel and gripping force characteristic curves are defined as follows:

Gripper stroke characteristic curve
The relationship between the gripper stroke SG and the drive stroke SA. The functional relationship is referred to as a mechanical transfer function.

Gripping force characteristic curve
The dependence of the ratio FG/FA (FG gripping force, FA driving force) on the drive stroke. This parameter is called the gear transmission ratio.

This example demonstrates that very large gripping forces can be produced within a rather limited physical range owing to the knee lever properties of the mechanics. However, the prehension force exhibits a different direction (before and after the dead centre of the knee lever motion) for the same direction of driving force. This is indicated in Figure 3.31 by the two regions 1 and 2. For comparison, Figure 3.32 shows an impactive gripper with a constant prehension force.

The toothed rack and pinion gear exhibits a uniform transmission. The prehension force characteristic curve $F_G/F_A = r_A/r_G =$ constant, and is independent of the relative posi-

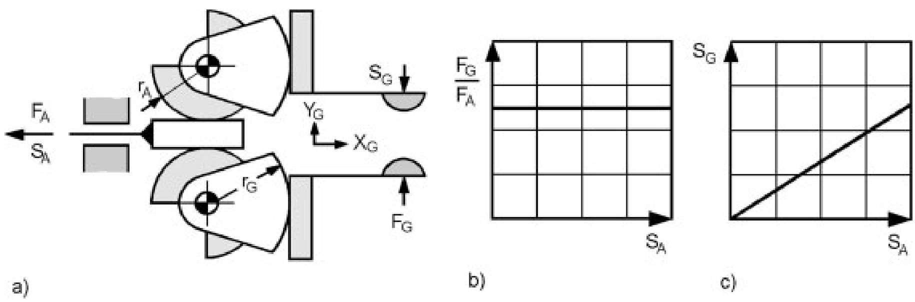


Fig. 3.32: Prehension force dependence for a parallel jaw gripper
a) kinematic model, b) prehension force dependence, c) transfer function

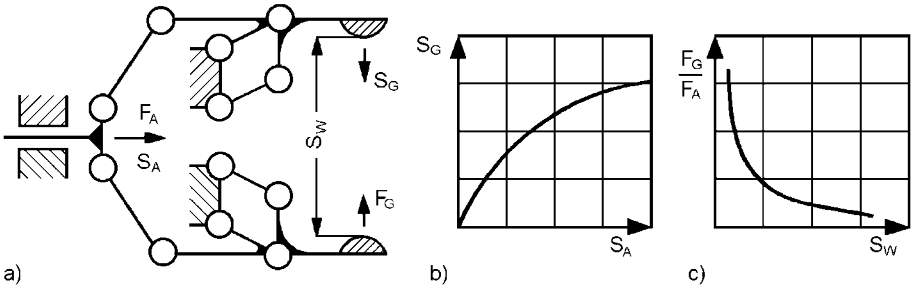


Fig. 3.33: Prehension force dependence for a gripper with circular translation of the jaws
a) kinematic model, b) transfer function, c) prehension force dependence,
S_w prehension range

tion of the gripper fingers. The transfer function is linear only for wheeled gears (many other gears have nonlinear characteristics).

For grippers like the one shown in Figure 3.33 the jaws remain parallel to one another though they move along a curved path. The effect of the knee lever on the gripping force can be seen in Figure 3.33 c).

The proportion of leverage affects the speed of jaw motion. The transmission ratio can be used to characterize this parameter.

> **Gear transmission ratio**
> Ratio of the actuator drive speed to the gripper jaw speed.

This parameter can change depending on the given kinematic solution:

- The gear transmission ratio is constant over the entire jaw travel.
- The gear transmission ratio increases or decreases during jaw travel.
- The transmission ratio exhibits a minimum or a maximum within the jaw travel.

In many cases it is desirable to have a gripper which orientates the workpiece in the gripper jaw centre, i.e. exhibits a self-centring effect. For the gripper depicted in Figure 3.34 the jaws are parallel and objects are guided linearly during the process of prehension and are finally positioned in the gripper centre axis [3-8]. The gripper construction is based on a six-link gear which is derived from the *Watt* chain.

For grippers resembling the one shown in Figure 3.34 a the points G and G' are guided approximately along a straight line while in the case of internal grippers, illustrated in Figure 3.34 b, the directing points of the gripper jaws are guided exactly along a straight line.

Another issue is the balance of the impactive prehension forces when a component is simultaneously gripped at several points. This happens in a purely mechanical manner for the kinematic design shown in Figure 3.35. The impactive jaws adjust themselves relative to the position of the workpiece. The relatively large number of joints poses some disadvantages though the use of two standard grippers with parallel jaws is an alternative.

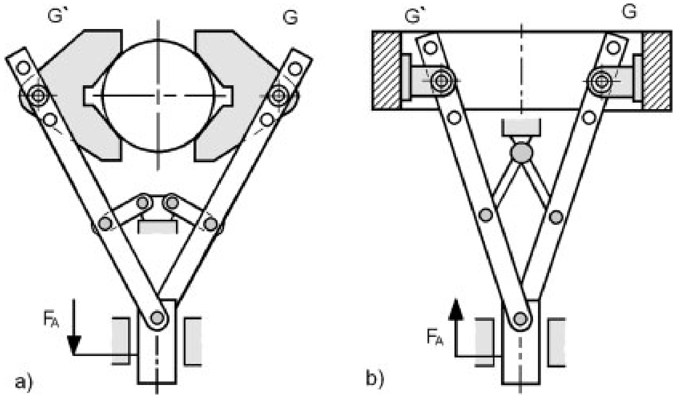


Fig. 3.34: Impactive grippers with centring effect
a) external gripper, b) internal gripper
F_A driving force

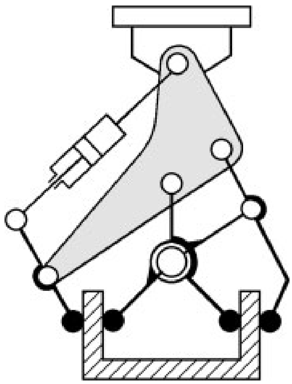


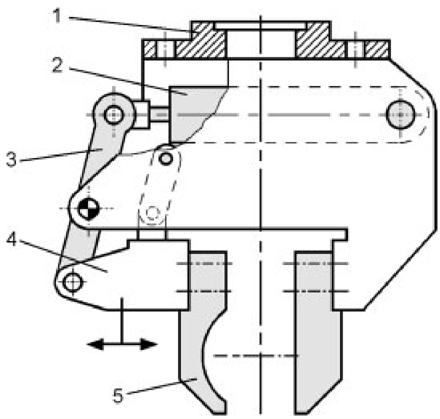
Fig. 3.35: Gripper with autonomous prehension force balance

3.2.1.1 **Parallel Impactive Grippers**

In addition to double movement parallel jaw grippers, there are also designs which rely on the movement of only one jaw. An example is shown in Figure 3.36. The function of this gripper is similar to that of a simple bench vice.

Grippers possessing only one mobile jaw enjoy a very simple construction. The device shown in Figure 3.37 a is driven by a linear pneumatic cylinder with relatively short stroke [3-9]. This cylinder is embedded in the housing and drives the mobile jaw. The return stroke is accomplished by a return spring within the cylinder. Integration of sensors for end of stroke detection is trivial. This form of gripper is robust and can support large gripping forces.

The second example (Fig. 3.37 b) shows the use of a rotary pneumatic cylinder. The linear motion of the piston inside the cylinder may be converted mechanically into rotational motion as an alternative to pneumatic rotary vane drives.



1 flange
2 hydraulic or pneumatic cylinder
3 lever
4 joint link
5 moving gripper jaw

Fig. 3.36: Gripper possessing one fixed and one mobile jaw

A great variety of pneumatic and electromagnetic prime movers (motors and gears) have been developed for driving parallel jaw grippers. In order to achieve the desired motion characteristics complicated gear mechanisms are often required, a selection of which are presented in Figure 3.38. With most grippers, jaw motions are synchronized, i.e. closure is achieved towards the centre in a uniform manner. However, as can be seen in the gripper shown in the left bottom picture, independent jaw motion is possible. This has some advantages where object centring is required as the gripper jaws autonomously adjust themselves with respect to the exact grip position. The only disadvantage lies in the fact that the compliance of the jaws is dependent on the pneumatic pressure supplied to each of the two cylinders.

It should be kept in mind that the prehension reproducibility depends to a great extent on the kinematics. The degree of mechanical play is proportional to the number of links in the force flow. Furthermore, expected operational lifetime is considerably reduced in situations of excessive mechanical play.

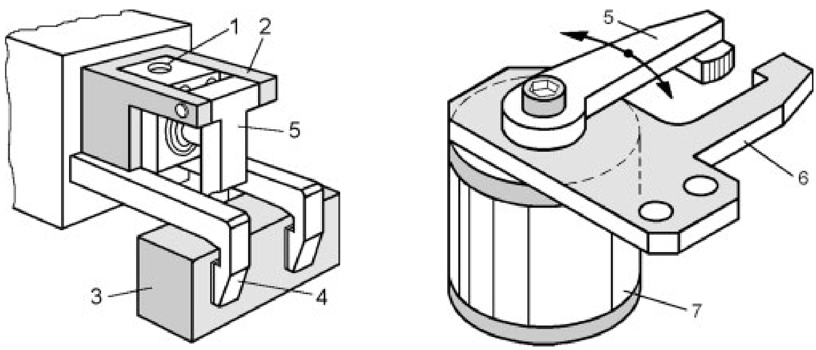


Fig. 3.37: Grippers with one mobile jaw: a) with linear actuation, b) with rotary actuation
1 pneumatic connection, 2 housing construction, 3 object for prehension, 4 retention constraint, 5 gripper jaw, 6 fixed finger, 7 rotating piston actuator (mobile finger)

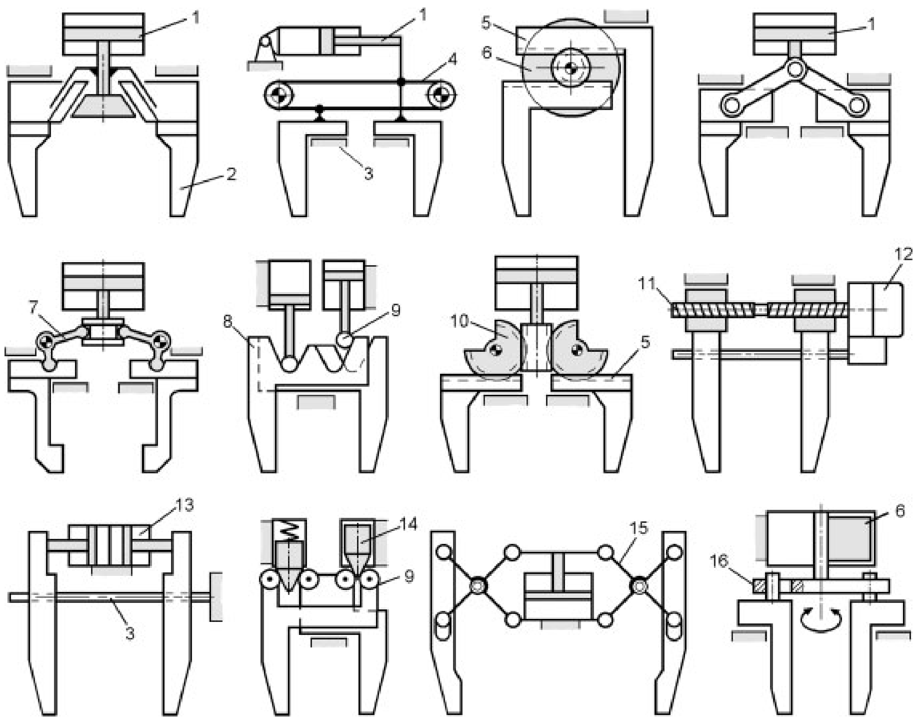


Fig. 3.38: Standard gripper drives for parallel grippers
1 pneumatic cylinder, 2 gripper finger, 3 straight line guide, 4 toothed belt, 5 toothed rack,
6 rotary pneumatic cylinder, 7 angle lever, 8 cam slide, 9 roller, 10 gear segment,
11 right-left handed thread spindle, 12 gear motor, 13 two cylinder arrangement,
14 pneumatic piston, 15 scissor gear, 16 cam disk with a groove

Each of the grippers shown in Figure 3.38 achieves jaw closure by parallel translation along a straight line. Further gear versions are shown as kinematic schemes in Figure 3.39.

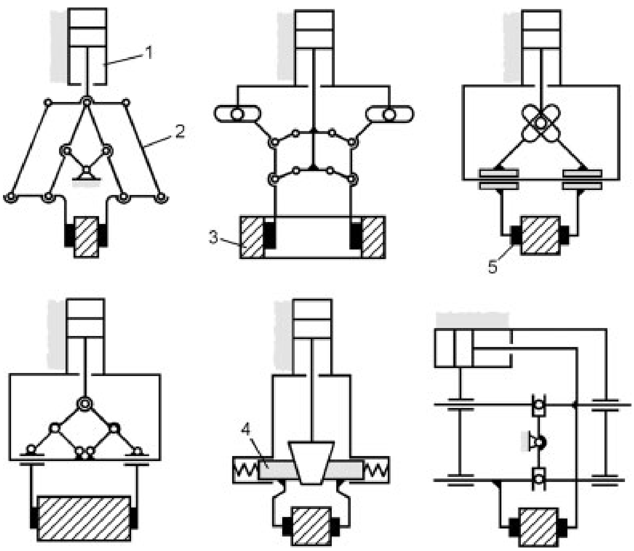
Though the kinematic models are independent of drive type, the commonest forms of prime movers used in grippers are pneumatic actuators.

Figure 3.40 shows some relevant calculation approaches for the gripping force F which will be used for the following example.

Example: Determine the internal diameter of the pneumatic cylinder required for the given kinematics and the prehension task described in Figure 3.41.

Specifications:

workpiece mass	$m = 1$ kg
safety factor	$S = 2$
acceleration in the z-axis	$a = 8$ m/s^2
friction coefficient	$\mu = 0.15$
pneumatic pressure	$p = 6$ bar



1 pneumatic cylinder
2 lever arm
3 workpiece
4 cam slide
5 gripper jaw

Fig. 3.39: Technical principles for impactive grippers with parallel jaw closure

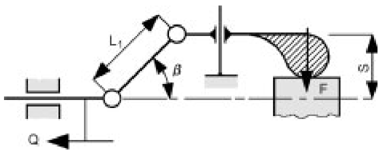
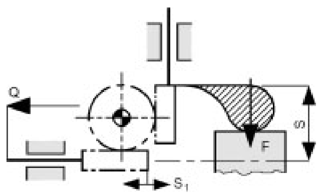
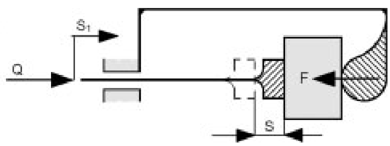
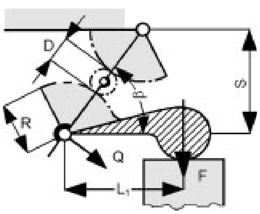
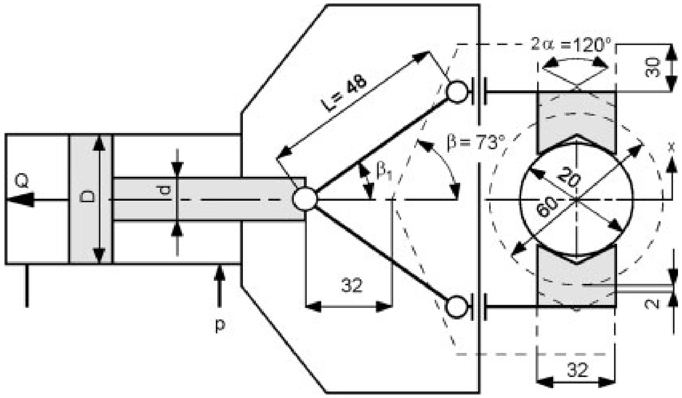
	$F = \dfrac{Q \cdot \tan\beta}{2}$ $S = L_1 \cdot \sin\beta$
	$F = \dfrac{Q}{2}$ $S = S_1$
	$F = Q$ (constant S) $S \equiv S_1$
	$F = \dfrac{Q \cdot (2 \cdot R + D)}{L_1}$ $S = \sin\beta \cdot (2 \cdot R + D)$

Fig. 3.40: Calculation of gripping force for gears with linear translation



d piston rod diameter
D piston diameter
Q piston force
p pressure

Fig. 3.41: Kinematics and example specifications

The following value for gripping force F_G is obtained from the equation given with Figure 2.45:

$$F_G = \frac{m\,(g + a)}{2 \cdot \mu} \cdot \sin\alpha \cdot Si = \frac{1\,\text{kg}\,(9{,}81\,\text{m/s}^2 + 8\,\text{m/s}^2)}{2 \cdot 0{,}15} \cdot \sin 60° \cdot 2 = 103\,\text{N}$$

According to Figure 3.40 the following equation applies for a gear with parallel guidance of the gripper fingers:

$$F_G = \frac{Q \cdot \tan\beta_1}{2} \rightarrow Q = \frac{2 \cdot F_G}{\tan\beta_1}$$

The angle β_1 is obtained from the design dimensions using the following steps:

$$\sin\beta = \frac{x}{L} \rightarrow x = 0.956 \cdot 48\,\text{mm} = 46\,\text{mm}$$

Subtraction of 30 mm for jaw travel gives:

$$\sin\beta_1 = \frac{(46 - 30)}{L} = \frac{16}{48} = 0.33 \rightarrow 19°$$

Hence, for the driving force Q

$$Q = \frac{2 \cdot 103\,\text{N}}{\tan 19°} = \frac{2 \cdot 103\,\text{N}}{0{,}344} = 598{,}8\,\text{N}$$

Assuming an atmospheric pressure P_a of 1 Bar (often 1.2 Bar is taken to allow for atmospheric pressure variations), the selected pneumatic cylinder will need an internal diameter of $d = 40$ mm and a stroke of 40 mm (external piston rod diameter of 12 mm). The maximum (theoretical) force on the piston rod side amounts to:

$$F_{zyl} = (p - p_a) \cdot A = 5\ \text{bar} \cdot \frac{\pi}{4}(D^2 - d^2) = 5 \cdot 10^5\ \frac{N}{m^2} \cdot \frac{\pi}{4}(0.04^2 - 0.012^2)\ m^2 = 572\ \text{N}$$

Should a 40 mm diameter cylinder be unavailable then the next size up is normally chosen. Alternatively, the needed criteria may be reached by reducing the safety factor.

Figure 3.42 shows simplified schemes of some design solutions for the transmission of the drive motion to the gripper fingers and jaws, respectively. For the solution depicted in Figure 3.42 a a second, identical but reversed cam slide is present for movement of the right gripper finger. Hence, the gripper jaws move synchronously towards one another. Two pneumatic pistons coupled to each another, and connected with the finger through a roll and lever, are activated in sequence as shown in Figure 3.42 b. For external prehension, the piston rod moves downwards.

The piston motion in Figure 3.42 c is transmitted to the gripper finger by an angle lever. The ball bearings used for the linear guidance simply reduce gripper jaw friction.

As previously mentioned, the closing velocity of pneumatically driven grippers should not be too high in order to avoid overload and damage through shock effects on joints and

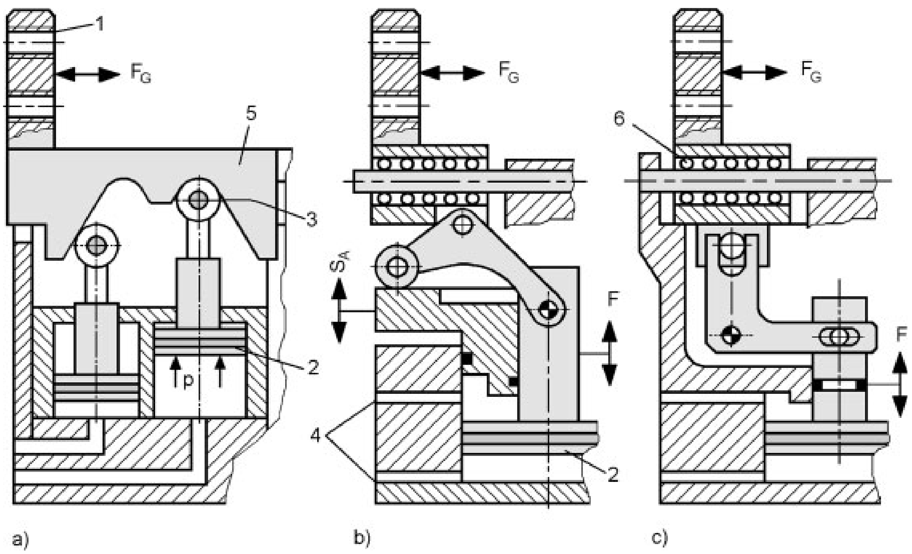


Fig. 3.42: Parallel jaw gripper with pneumatic drive
a) separate single acting piston drive for opening and closing
b) double acting piston drive (SMC)
c) angle lever transmission
1 basic jaw, finger, 2 piston, 3 roller, 4 compressed air connection,
5 cam slide, 6 straight line guide
F_G gripping force, F piston force, p pressure, S_A piston stroke

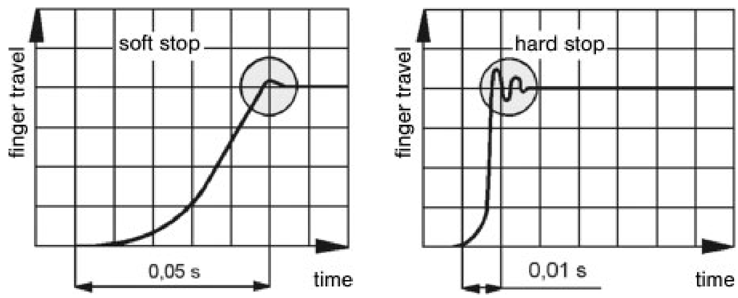


Fig. 3.43: Too short closing times lead to shock overload to moving gripper elements.

fingers as the end stop is reached (Fig. 3.43). Consequently, choke valves should be provided to regulate air flow velocity. Such valves are integrated into many pneumatic grippers and the adjustment starts with an almost closed regulating stop valve.

Gripper fingers are heavily loaded and inappropriate dimensioning of the cross section and shape of the mechanical parts may lead to permanent fracture at points under high mechanical stress. The use of circular chamfers can help reduce the likelihood of fatigue fractures at corners (Fig. 3.44) but this cannot be totally ruled out. Profile optimisation using CAO (*Computer Aided Optimization*) methods is one recommended option [3-10].

An optimized profile leads to a more uniform stress distribution over the component surface, achieved by increasing the area of the overloaded regions and decreasing the area of the underloaded regions. This subject was first dealt with as early as 1934 (without the help of a computer) [3-11]. The starting point of the CAO method is a FEM structure of the component. The nodes of the mesh shift under load. The resulting *van Mises stress* is displayed in a similar manner to a temperature distribution in which the places with the heaviest mechanical stress are represented in the same way as “hot spots” in a thermal plot. Several iterations may be required to achieve an optimised mesh.

In addition to the finger shape, the guidance of the finger in the gripper housing also plays an important role. The following properties deserve special attention:

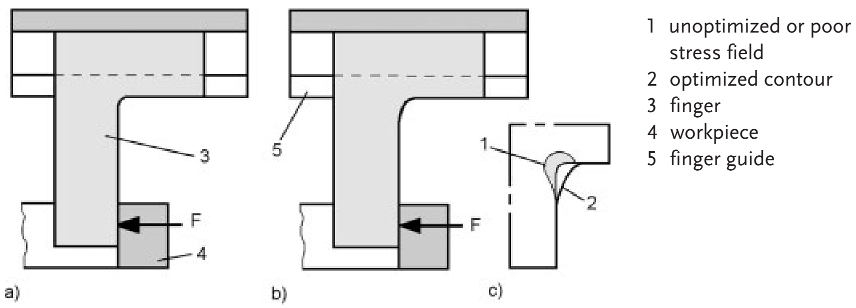


Fig. 3.44: An example of finger optimization (internal grip)
a) unoptimized shape, b) optimized shape, c) contour at the critical region

- friction conditions
- motional behaviour
- contact deformation
- wear performance
- surface pressure in the guideways
- displacement of guideway surfaces

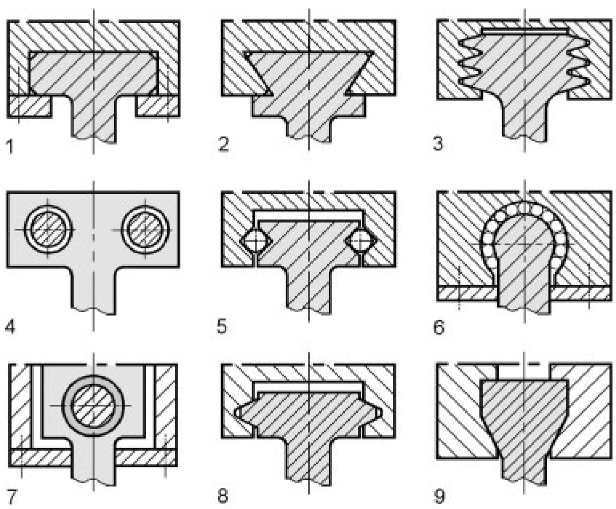
The guidance of the jaws can be realized by
- slide and roller bearings
- round and multi-sided guides

Rotary joints tend to be more cost effective than slide guides. They are practically free from friction and the probability of seizing is very low. In combination with selected lever drives they make the design of mechanical grippers capable of good linear slide motion easier.

For simple low cost straight line guidance, mounting in journal bearings or brass bushes may provide adequate freedom of movement with low impact sensitivity. For designs using longer fingers, roller guides are best used as they provide lower friction and are free from stick-slip effects. In all cases, reduced friction means increased efficiency and longer life.

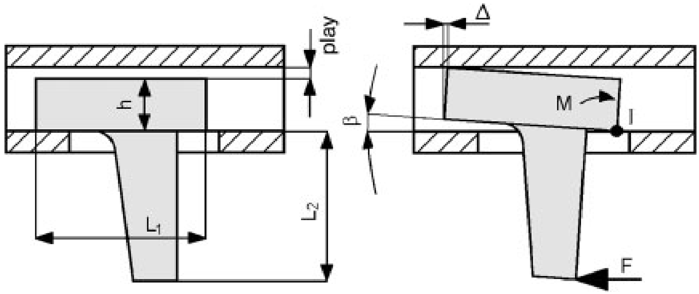
Figure 3.45 shows some practical finger guides.

In order to ensure smooth finger movement it is necessary to minimise the amount of play in the guidance slide bearings. The force F acting on the finger produces a torque M which leads to tilting of the finger and the jaw, respectively (Fig. 3.46). This torsional moment is present in all guide types when forces are not aligned with the mass centre of gravity. The smaller the angle of tilt β, the weaker the force components contributing to "hitching" of the slide in the guide at point I. The tilt angle decreases with increasing ratio of the bar length L and height h (L/h).



1 flat guide
2 dovetail guide
3 multiple-tooth guide
4 double round guide
5 ball guide
6 open round roller guide
7 round guide
8 rooftop guide
9 trapezoidal guide

Fig. 3.45: Some examples of finger guides

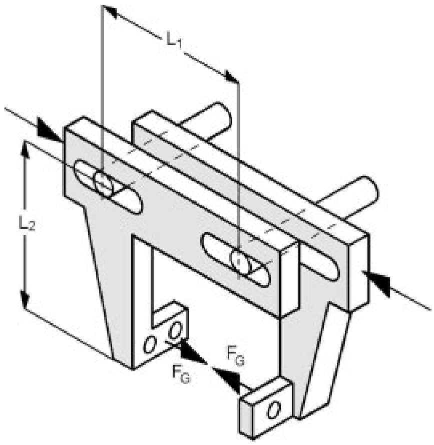


M moment
K force

Fig. 3.46: Tilting of gripper fingers in a straight line guide (guide ratio $L_2 : L_1$)

Figure 3.47 shows a design example which improves the support of the gripper fingers. To this aim, the guideway length L_1 is increased (see also Fig. 3.50).

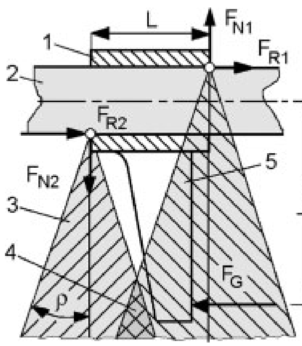
The wear of the sliding surfaces is also affected by the guide play. Strong tilting of the jaws parts, to which the gripper fingers are attached, leads to punctiform contact forces at the support points. This increases the surface pressure and can eventually lead to chatter marks and consequently to premature wear out. The advantages of a longer and broader surface guide are somewhat offset by a heavy gripper construction.



L_1 separation of the guide pins
L_2 finger length
F_G gripping force

Fig. 3.47: Improvement of the guide ratio $L_2 : L_1$

Large guideway lengths and small guideway frictional coefficients makes it possible to use long fingers without the danger of seizure. The general mechanical relationships are demonstrated for a simple cylinder guide in Figure 3.48. When this guide is subjected to a load, the friction angle ϱ at the resulting points of support may be noted. The slide 1 is likely to seize as soon as the line of prehension force F_G passes through the overlap area 4 of the two friction cones 3. Consequently, the allowable finger length L_F depends, to a first approximation, on the friction coefficient μ ($\mu = \tan \varrho$) and the guideway length L of the slide.



1 slide
2 round guide (diameter, d)
3 friction cone
4 overlap area
5 finger

F_G prehension force
F_R friction force
F_N support force
ϱ friction angle
L guide length
L_F finger length

Fig. 3.48: Forces acting in a cylinder guide

From the following three equilibrium equations:

$$\Sigma F_x = 0 = + F_{R1} + F_{R2} - F_G \tag{3.31}$$
$$\Sigma F_y = 0 = + F_{N1} - F_{N2} \tag{3.32}$$

therefore $F_{N1} = F_{N2} = F_N$ and hence also $F_{R1} = F_{R2} = F_R$

$$\Sigma M_{(II)} = 0 = - F_{R1} \cdot d + F_{N1} \cdot L - F_G \cdot (L_F - (d/2)) \tag{3.33}$$

Substituting $F_R = F_N \cdot \mu$ and $F_G = 2 \cdot F_R$ from (3.31) into (3.33) gives:

$$F_N \cdot \mu \cdot d - F_N \cdot L + 2 \cdot F_N \cdot \mu(L_F - (d/2)) = 0 \tag{3.34}$$
$$\mu \cdot d - L + 2 \cdot \mu \cdot L_F - 2 \cdot \mu \cdot (d/2) = 0$$

from which the guide length can be obtained in (3.35)

$$L = 2 \cdot \mu \cdot L_F \tag{3.35}$$

$L < 2 \cdot \mu \cdot L_F$ will result in slip-stick activity in the socket while for $L > 2 \cdot \mu \cdot L_F$ it should glide freely. Seizure or free sliding is hence independent of the shifting force F_G.

A gripper with a multitooth finger guide, schematically shown in Figure 3.49, is another interesting and very effective solution.

This design is a parallel arrangement of several narrow prismatic guides. Narrow guides permit easier design of a favourable guide ratio L/H (guide length to guide height) thus counteracting slip-stick effects. At the same time the forces and moments are distributed over several guiding surfaces thus reducing surface pressure. Since the wear of a guide depends on the hardness of its components, surface pressure, dirt and lubrication, this form of straight line guide solves a number of potential problems. The jaws are lapped in order to ensure a very small play (0.01 mm) within the guide.

In order to achieve a favourable guide ratio (finger length to guide length of the gripper jaws), the gripper shown in Figure 3.50 possesses a guideway length which is doubled in

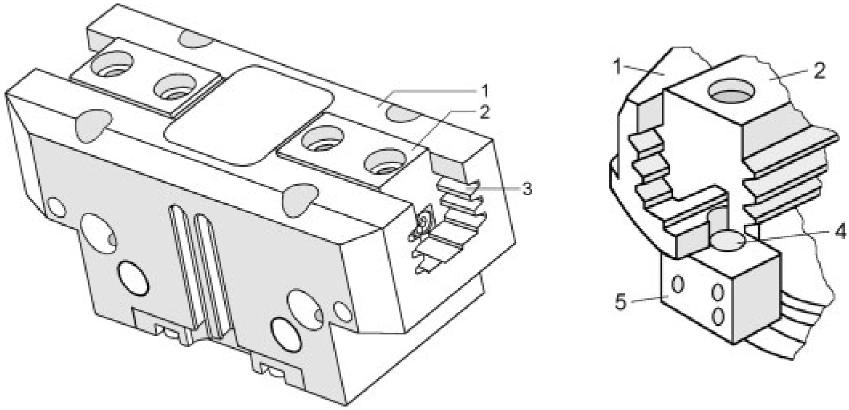
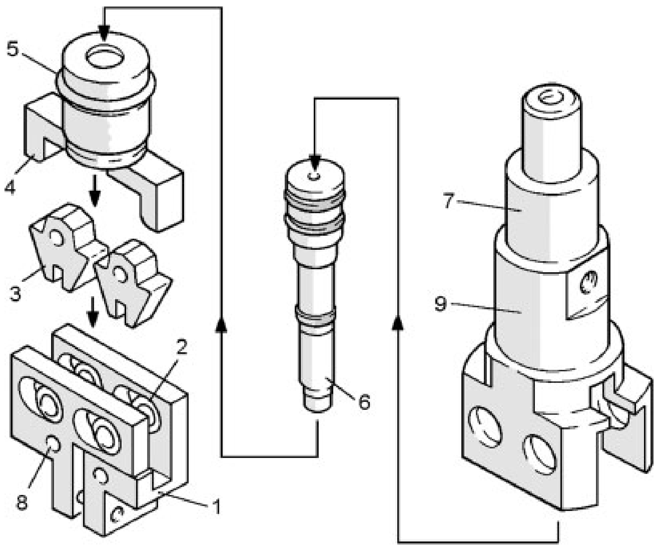


Fig. 3.49: Robust universal gripper with precision multitooth guide available in eight installation sizes (*Schunk*).
1 gripper housing, 2 jaw, 3 multitooth guide slide bearing, 4 opening for sensor installation, 5 sensor holder

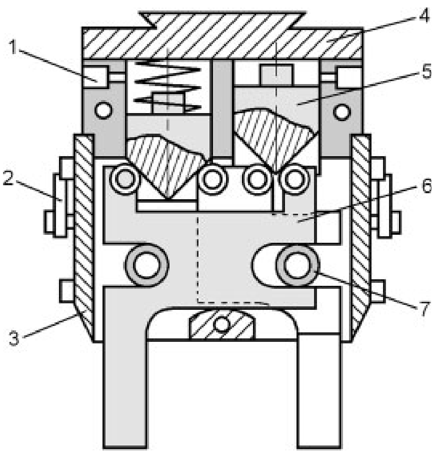
comparison to similar designs. The guidance of the fingers has already been described in Figure 3.47.

Each finger is free to move on rollers within the guides. The fingers symmetrically overlap. Nevertheless they are sufficiently wide for the mounting of the gripper jaws. The fingers are activated by rocker arms. The large piston presses against the rocker arm to close the finger and the small piston is activated to release the finger. The rod of the smaller piston passes through the larger piston and pushes against the internal surface of the rocker arm.



1 gripper finger
2 roller guide and axis
3 rocker arm
4 pressure bridge
5 piston for clamping
6 piston for releasing
7 mounting scheme
8 pins
9 cylindrical body

Fig. 3.50: Parallel gripper (patented: Manz-Automation)



1 compressed air connections
2 clamping piece
3 holder for the endstop position sensor
4 cover
5 pneumatic piston
6 gripping finger or jaw
7 guide roller

Fig. 3.51: Internal construction of a parallel jaw gripper (*Montech*)

Figure 3.51 shows a gripper, each finger of which is actuated by a pneumatic piston. A return spring ensures that the gripper jaws are open in the unpressurized state.

If the spring is mounted on the other piston then the gripper jaws are closed in the absence of pressure which is relevant to its application as an internal gripper. The gripper fingers are guided against the rollers with negligible friction and arrival at the end positions can be detected by laterally mounted sensors.

A pressure maintaining, or double-check, valve can be mounted in the pneumatic circuit to secure the prehension force, as illustrated in Figure 3.52. This ensures that the retention force remains constant. To ensure rapid response, such valves should be mounted as close to the gripper as possible.

Figure 3.53 shows a simplified model of such a gripper design intended for precision assembly tasks. The parallel gripper jaws are driven by pneumatic cylinders, the two pistons being coupled through a rack and pinion gear so that the jaws close exactly in the middle.

Prehension is determined by the operating pneumatic pressure. For an absolute pressure of 6 bar (atmospheric pressure taken as 1 Bar) and piston diameter of 12 mm a force of 56 N is generated. Integrated return springs are augmented by a third spring which serves to reduce backlash. The prehension forces depend on the actual design (single act-

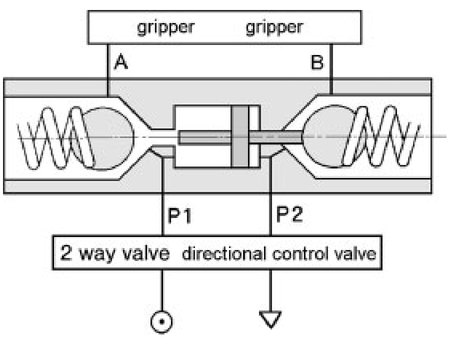
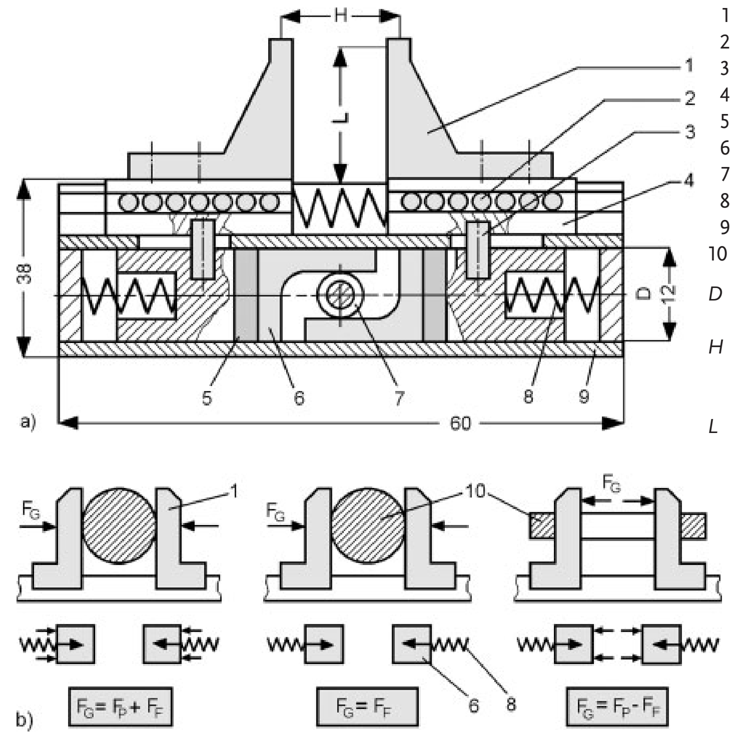


Fig. 3.52: Securing the gripping force with the help of a stop valve



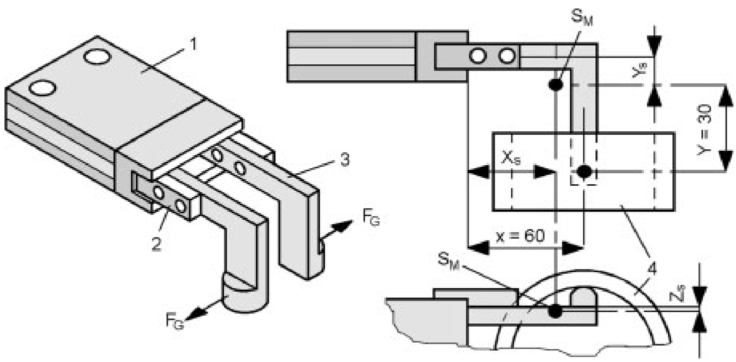
1 gripping finger
2 roller guide
3 engaging pin
4 gripper jaw
5 seal
6 pneumatic piston
7 cog wheel
8 return spring
9 gripper housing
10 workpiece

D piston diameter (12, 16 or 20 mm)
H total travel (5, 10 or 15 mm depending on the overall size)
L working distance

Fig. 3.53: Precision gripper with roller guide (*Festo*)
a) sectional view, b) active forces

ing cylinder with return spring, double acting cylinder etc.). Figure 3.53 b shows the contribution of the individual active forces for various configurations.

Example: Prove if the gripper shown in Figure 3.54 is applicable for handling a ring with a mass $m_1 = 0.5$ kg. The mass of the gripper finger is $m_2 = 0.15$ kg.



1 gripper
2 jaw
3 gripper finger
4 workpiece
S_M centre of mass

Fig. 3.54: Parallel jaw gripper with eccentric gripping points

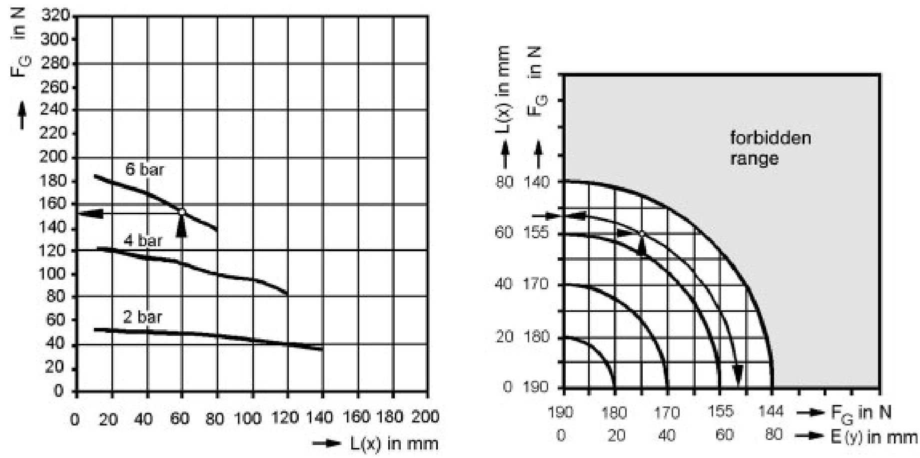


Fig. 3.55: Load capacity for an example parallel jaw gripper
F_G gripping force at 6 bar, $L_{(x)}$ lever arm, $E_{(y)}$ eccentricity

The dimensioning of the gripper specified by the supplier provides some limits which must be observed. There are separate load diagrams supplied by the manufacturer which are valid for the specific gripper and depend on its type and size.
The characteristic curves for the gripper shown in Figure 3.54 are given in Figure 3.55.
The mass centre S_M of the gripper finger has the following dimensions:
$x_s = 50$ mm, $y_s = 8$ mm and $z_s = 3$ mm.
Initially, the required gripping force F_G will be estimated.

$$F_G = \frac{m_1 \cdot g \cdot S}{2 \cdot \mu} \tag{3.36}$$

S safety factor (S = 2 to 4)
g acceleration due to gravity 9.81 m/s^2
μ coefficient of friction (metal-metal $\mu = 0.15$)

$$F_G = \frac{0.5 \cdot 9.81 \cdot 4}{2 \cdot 0.15} = 65.4 \text{ N}$$

Now this value must be checked against the lever arm – gripping force graph to ascertain whether such a gripping force is allowed or not. If the eccentricity is ignored, the gripper can deliver a gripping force of $F_G = 155$ N for a working pressure of 6 bar. Taking into account the eccentricity y and the lever arm length x, with help of the second graph proceed as follows:

- draw a vertical line through $E_{(y)} = 30$
- draw a horizontal line through $L_{(x)} = 60$
- draw a circular arc of radius origin – point of intersection x–y
- read off the gripping force $F'_G = 150$ N

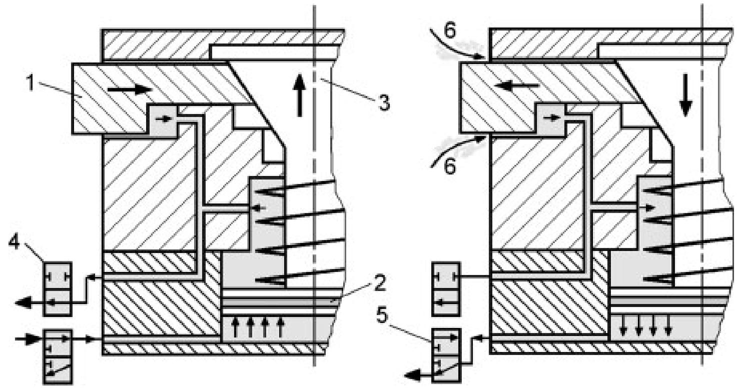
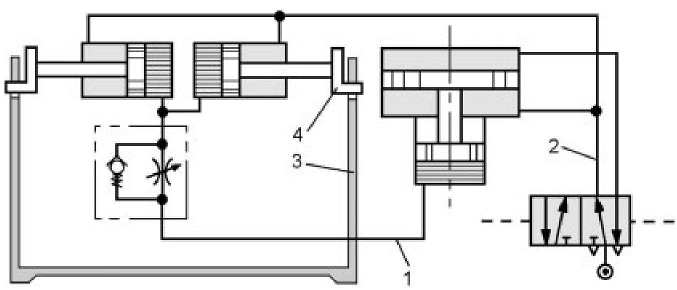


Fig. 3.56: Two-finger parallel gripper with hydraulic drive (*Schunk*)
1 gripper housing, 2 jaw, 3 gripper finger, 4 object, 5 pressure control valve used as a sequence valve, 6 alternating check valve (or-valve), 7 storage, 8 4/3 direction control valve, 9 rack and pinion gear

Since F'_G does not exceed F_G, the gripper is applicable for the given handling task. In case the point of intersection x–y lies in the forbidden range, an alternative gripper must be selected. The static and dynamic torques must also be considered, taking into account the finger mass and the separation of mass centres (x_s, y_s) for both fingers.

Very large prehension forces may require hydraulic drives. Figure 3.56 shows a hydraulic gripper with a travel of 120 mm. For an oil pressure of 60 bar and finger length of 100 mm it develops a prehension force F equal to 1.65 kN. The retention force is maintained by integrated disk springs in case of sudden pressure drops. Filtered hydraulic oil (10 μm) serves as an active fluid medium. The total finger travel for a specified closing and opening time of 1.3 s requires a volume flow of 2.5 l/min.

Proportional control is very difficult (though not impossible) to achieve by pneumatic means. In circumstances where a complete hydraulic solution is undesirable, a form of pneumatic to hydraulic conversion may be used. This employs the normal compressed air supplies and maintains the hydraulics within a separate closed system as shown in Figure



1 hydraulic circuit
2 pneumatic circuit
3 object, e.g. a case with an opening for gripping
4 gripping clasp (finger)

Fig. 3.57: Pneumatic-hydraulic gripper drive

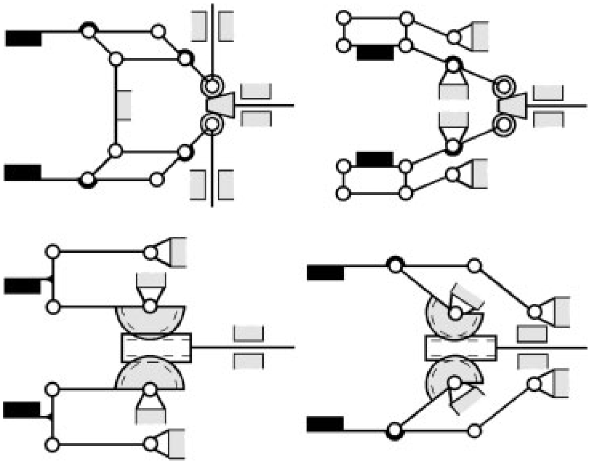


Fig. 3.58: Gripper mechanisms with circular translation of parallel gripper jaws by means of curved joints

3.57. Additional force may also be achieved by using pneumatic pressure boosters but they tend to be complicated and expensive.

Gripper jaws may close in a manner which maintains them parallel to one another despite either the prime mover, or an inter connecting link, being subject to purely rotational movement. Some kinematic models are shown in Figures 3.58 and 3.59.

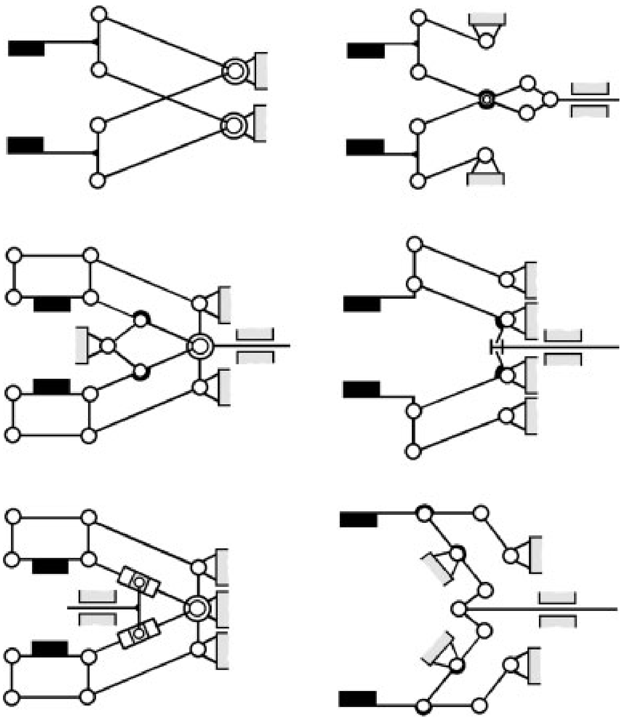


Fig. 3.59: Gripper mechanisms with circular translation using slide and rotary joints.
(A kinematic chain consists of a number of links and connecting joints.
If a frame and a drive link are set up, the kinematic chain is referred to as a mechanism)

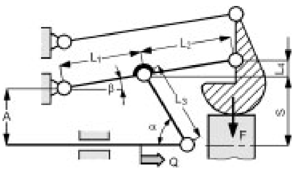
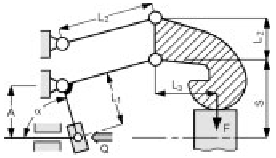
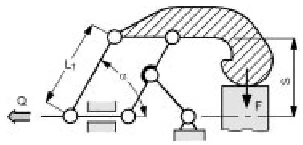
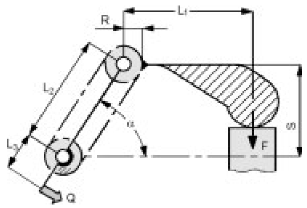
	$F=\frac{Q}{2}\cdot\frac{L_1\cdot\sin(\alpha+\beta)\cdot\cos\beta}{(L_1+L_2)\cdot\cos\alpha}$ $\sin\beta=\frac{L_3\cdot\ \sin\alpha+A}{L_1}$ $S=A+(L_1+L_2)\cdot\sin\beta-L_4$
	$F=\frac{Q\cdot A}{2\cdot L_2\cdot\sin\alpha}$ $S=A+L_2\cdot\sin\alpha$
	$F=\frac{Q\cdot\tan\alpha}{2}$ $S=L_1\cdot\sin\alpha$
	$F=\frac{Q\cdot L_3\cdot R}{L_2\cdot L_1}$ $S=\sin\alpha\cdot L_2$

Fig. 3.60: Kinematic models of some lever gears with rotary translation of the gripper jaws
Q driving force, *F* gripping force, *S* jaw travel

The force may be transmitted to the jaws by rotary joints (including toothed wheel gears) or by translational slide joints. However, the presence of many joints introduces excessive backlash making such designs undesirable in terms of precision.

The transmission of the gripping force to the gripper jaws can be realized in different ways as illustrated by the examples shown in Figure 3.60.

The design of such grippers will be illustrated in the following by presenting several examples. The gripper depicted in Figure 3.61 utilizes a short travel pneumatic cylinder (9), the housing of which is additionally provided with toothed racks on both sides (10). The jaw motion is produced by a toothed rack and pinion gear (2, 10). This, in connection with a double crank mechanism, results in circular motion of the jaws (5). The opening distance obtained using this principle is exceptionally large in comparison to other mechanisms. Since the pneumatic cylinder (9) is moving and the piston rod is firmly clamped, the compressed air is fed via air channels through the piston rod.

The toothed racks (10) can be attached to the cylinder housing using, for example, conventional slots. It is also possible to use a single-acting pneumatic cylinder if a return

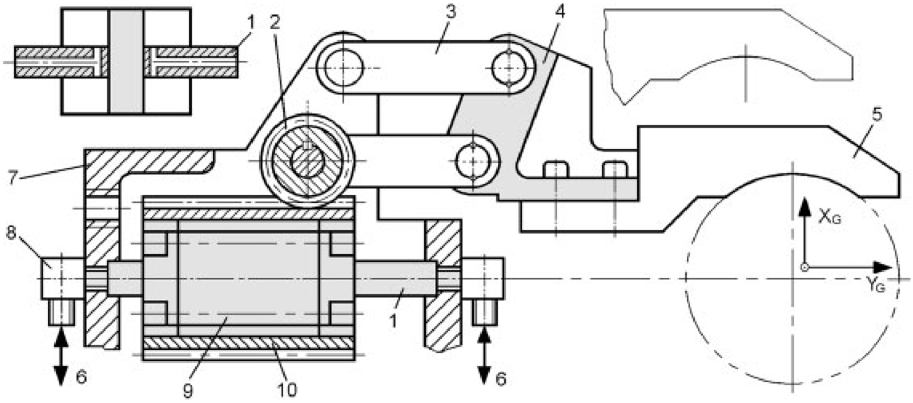


Fig. 3.61: Impactive gripper with rotary translation of the gripper jaws
1 piston rod, 2 toothed wheel, 3 lever, 4 mounting plate, 5 gripper jaw, 6 compressed air supply, 7 gripper housing, 8 angled compressed air connection fitting, 9 double action pneumatic cylinder, 10 toothed rack

spring is integrated into it. As is customary, the gripper jaws (5) are exchangeable and are prepared in accordance with the prehension contour of the workpiece. Some manufacturers also offer gripper jaws which are workpiece neutral and must be modified by the user. The rotary translation of the jaws leads to a displacement of the prehended object centrum, which, with parts of different size in the *y*-direction must be taken into account.

The basic concept behind the gripper shown in Figure 3.62 is to break down the opening mechanism into modular components in such a way that it is possible to design multi-finger grippers or collets for decoilers and similar equipment. It is noteworthy that the use

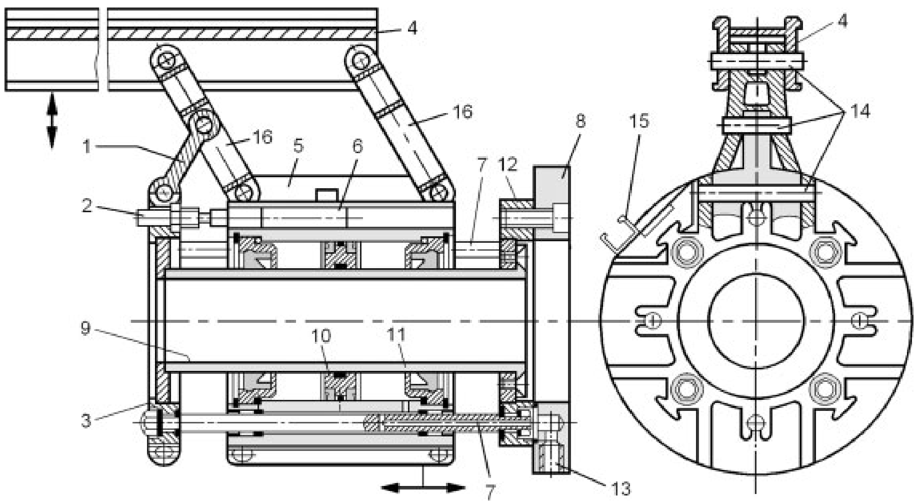


Fig. 3.62: Modular finger gripper (*GMG*)
1 crank arm, 2 hydraulic buffer, 3 head plate, 4 finger, 5 slide, 6 stop pin, 7 guide rod, 8 flange, 9 piston tube, 10 fixed piston, 11 cylinder cover, 12 base plate, 13 compressed air connection, 14 bolt, 15 rail for cables, transducers etc., 16 guide

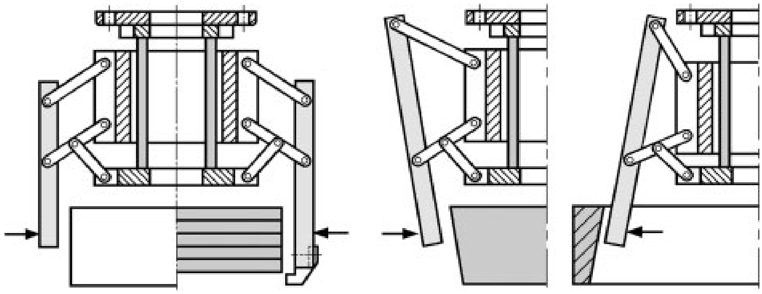
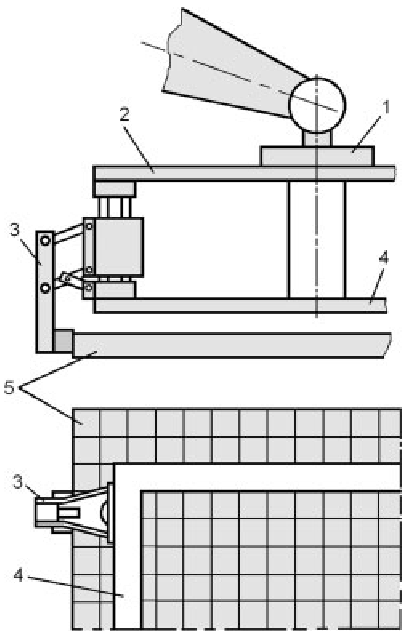


Fig. 3.63: Joint variations of a modular finger gripper

of a fixed ring piston (10) provides free access to the core which can be used to pass pneumatic tubes or cables for sensor integration etc. The gripper is built from extruded aluminium profiles which easily allow for different finger lengths (for internal or external prehension).

The example in Figure 3.62 shows the basic set-up for a 4-finger gripper where the air channels are integrated into the construction. The gripper fingers (4) must be additionally equipped with gripping and clamping jaws.

The finger geometry of the gripper configuration shown in Figure 3.63 is slightly different. This allows the handling of conical objects both internally and externally. Tilting of the fingers, within the technical limits of the mechanism, is possible solely by varying the points at which the joints are secured. The gripper is capable of clamping large objects and with the help of an underhook finger can also be made to handle laminated sheet objects.



1 robot flange
2 frame
3 single jointed finger
4 auxiliary frame
5 grid

Fig. 3.64: Prehension of light grids (*GMG*)

When using single fingers for the prehension of large but relatively light objects it is possible to design a suitable gripping system like the one shown in Figure 3.64. The separate fingers are attached to a frame and clamp on the outer contour of the object.

It is also possible to design gripper fingers which pass between the strands of woven wire mesh and cast grids. As with the internal prehension of thin-walled bodies, a multi-finger gripper has the advantage of being able to distribute the gripping force uniformly thereby avoiding significant deformation of the object. In the case of light pressed wire meshes, prehension can be achieved by using a number of such grippers, distributed over the surface of the mesh. For more rigid cast grids, the external prehension depicted in Figure 3.64 is more practical. For very light woven meshes, ingressive methods as explained in chapter 4 are more applicable.

The hollow interior of the gripper shown in Figure 3.65 permits prehension of parts which are delivered from magazine mandrels. Should it be possible to design the gripper with a lateral offset (rather than centred) flange, then the free inner space of the gripper allows access to parts stored on long spindles and magazine rods.

This form of prehension is analogous to the human four finger grip. The three lower fingers counteract the mass forces while the upper finger maintains object alignment. The gripper can operate along axles, spindles, and magazine rods.

Figure 3.66 shows a design of gripper capable of prehending two parts coaxially, a task which cannot be fulfilled by a single human hand. The 6-finger gripper is based on a special aluminium profile for the finger and its interior zone. It is pneumatically actuated by an integrated cylinder with a ring-shaped surface.

Prehension procedure: Initially the gripper grasps the bolt using 3 fingers. Then it is moved toward the ring element, pushes the bolt into the ring, and then releases it. Now the gripper closes again seizing both parts and carrying them to the mounting base. The displaced finger pairs cannot be moved independently by the single drive. Moreover, a degree of compliance should be included to compensate for the tolerances of the workpiece and the gripper. For the screwing of threaded parts, this gripper can be further extended. The inclusion of a rotary lead-through, integrated within the flange, makes indefinite rotation possible.

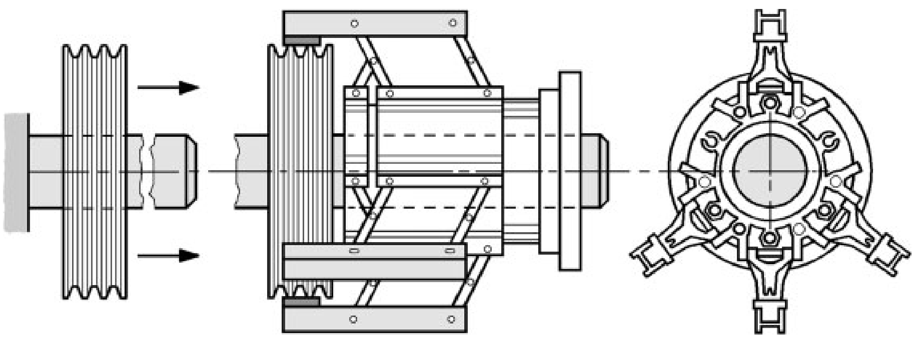
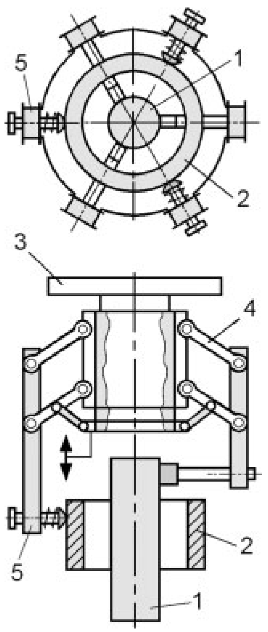


Fig. 3.65: Horizontal gripping of a V-belt pulley from a magazine mandrel (*GMG*)
Left: gripped object stored on mandrel; middle: gripper holding workpiece.
Right: gripper without workpiece



1 workpiece (bolt)
2 workpiece (ring)
3 gripper flange
4 linkage
5 gripper finger

Fig. 3.66: Coaxial double gripper (*GMG*)

Figure 3.67 shows the kinematic concept of a gripper designed to operate with a wide range of object sizes (from 25 to 170 mm) without the need to change the fingers. The gripper fingers are synchronously guided by a rhomboid-lever gear. Driven from a pneumatic cylinder, the motion of the gripper jaws forms a circular translation.

A large adaptable gripping range can be also realized using spindle drives integrated with position encoders and computer control. Though spindle drives are much slower than pneumatic actuators, some time is saved because not every gripping operation re-

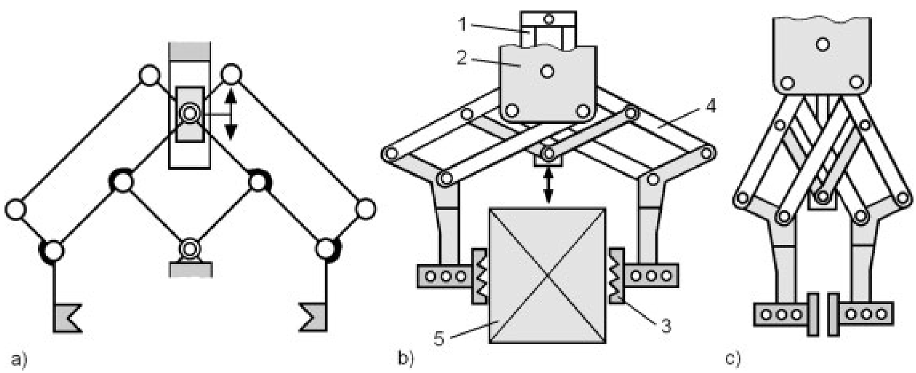
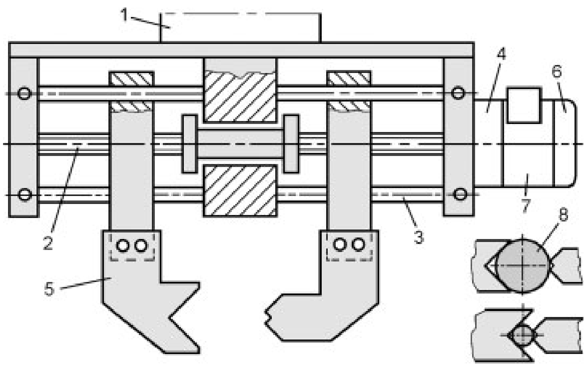


Fig. 3.67: Adaptable two-jaw gripper
a) kinematic model, b) design example, c) closed gripper
1 actuator, 2 housing, 3 gripper jaws, 4 linkage, 5 workpiece



1 base plate and flange
2 self-locking spindle
3 guide
4 gear box
5 gripper jaw
6 encoder
7 electric servo motor
8 workpiece

Fig. 3.68: Servo gripping system

quires jaw movement over the full range. Figure 3.68 shows such a gripper. The adjustment mechanism contains a double threaded (right and left handed) spindle with a self locking thread pitch. The holding prisms must be appropriately designed in order to allow for effective grasping of all possible components including the small round parts illustrated in Figure 3.68.

3.2.2 Angular Impactive Grippers

Angular (rotary and/or linear) grippers are characterized by grasping organs which open and close along a curved path. Operating ranges can be as wide as 90° which has the advan-

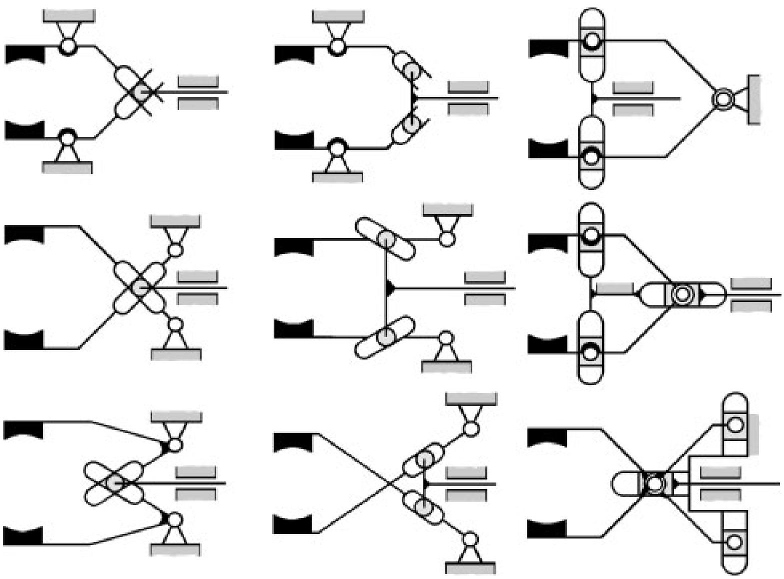


Fig. 3.69: Kinematic gripper models with 4 rotary and 3 linear joints achieving closure along a curved path

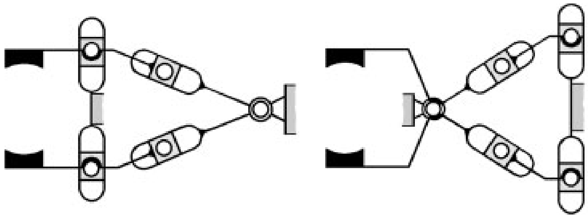


Fig. 3.70: Kinematic models of grippers with 4 rotary and 4 linear axes

tage of accommodating a wide range of potential objects but also, poses limitations when operating in restricted space. Grippers employing purely rotational motion of the fingers require only simple mechanics; they are reliable and can be cost effectively fabricated. Angular joints can be kinematically combined. The examples depicted in Figure 3.69 contain up to 4 rotary and 3 linear joints. Swivel joints can also be designed as double joints.

The gripper kinematics shown in Figure 3.70 are obtained by the addition of a linear joint. The extension to further kinematic models can be inferred from those given here. However, each design has its own merits depending on their implementation with real mechanisms. As a rule, the technical realization of rotary joints is simpler and cheaper than that of linear joints.

Each of the kinematic examples in Figure 3.71 contains 5 rotary joints and 1 linear joint which is solely used for coupling to the drive. If a linear actuator, e.g. a pneumatic cylinder, is used then this linear joint would normally be part of the cylinder.

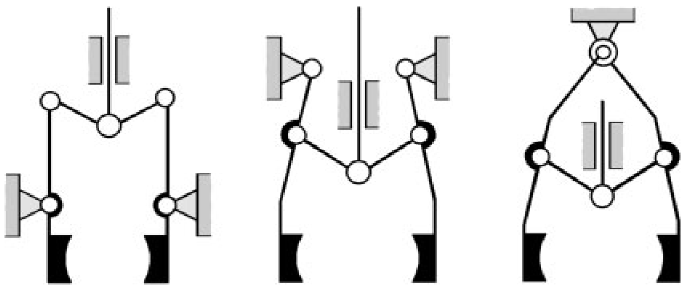


Fig. 3.71: Kinematics of an angular gripper with 5 rotary and 1 linear joints

Figure 3.72 shows some kinematic options containing 6 rotary and 1 or 2 linear joints. Further enhancements to these basic models are possible but it should always be remembered that the larger the number of joints the greater the degree of mechanical play at the end of the chain (usually the prehension point).

Figure 3.73 shows the gear system for an angular gripper having four links. The motion transmission is realized by a toothed rack and two gear segments. The pictorial procedure illustrates the transition from a general to a more specific structure, and finally to a practical design.

Figure 3.74 shows several further kinematic models for grippers employing toothed segments. The gripper fingers can also be designed as spring joints. These are rotary

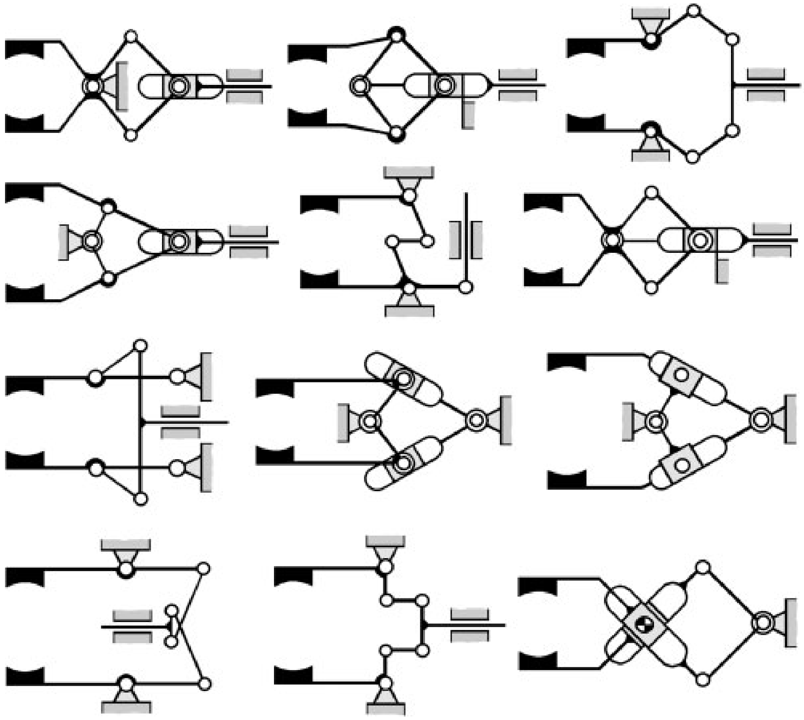


Fig. 3.72: Kinematic models of impactive grippers closing along a curved path and possessing 6 rotary joints and 1 or 2 linear joints

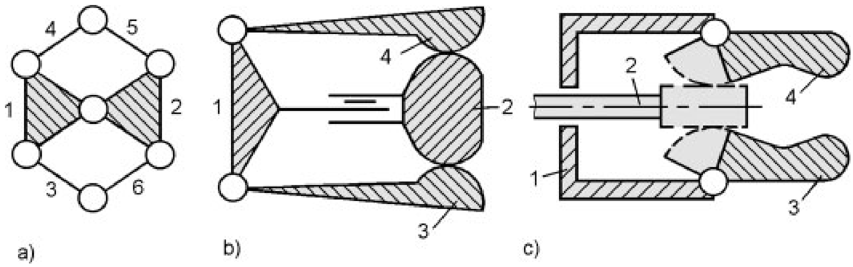


Fig. 3.73: Gripper gear with toothed rack and gear segments
a) kinematic chain containing six links, b) special structure, c) linear gripper with four links
1 base frame, 2 driving link, 3 and 4 gripping links

joints using well matched materials. Depending on the design, the actuation can be translational or rotational (e.g. pneumatic turret drive or an electric motor).

The diversity of realizable gripper designs is as great as the number of possible kinematic models, some examples of which are depicted in Figure 3.75. The gripper with the flexible semi-prism (bottom right) can reliably hold parts of different diameter without displacement of the prehension centre (Soviet Patent 682 366, MK B25 J 15/00).

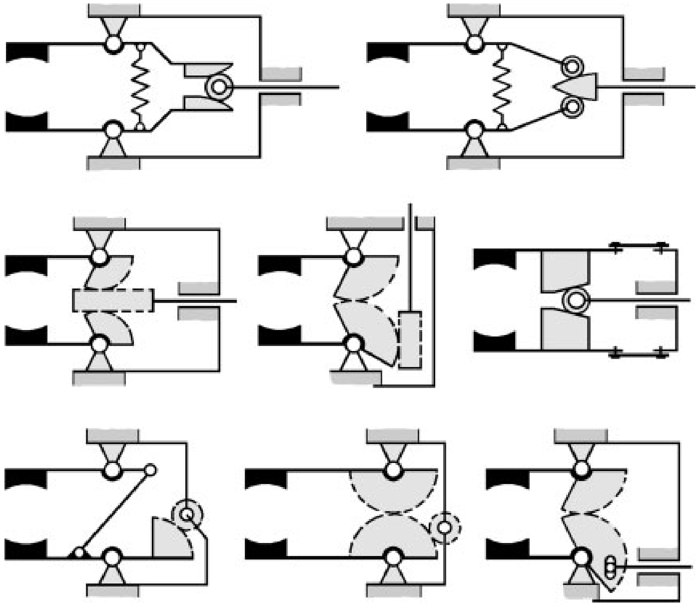


Fig. 3.74: Curved joints in angular grippers

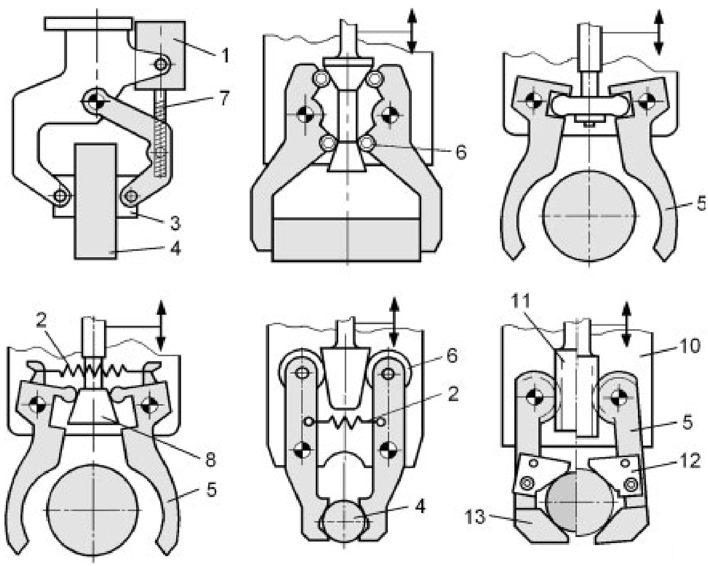
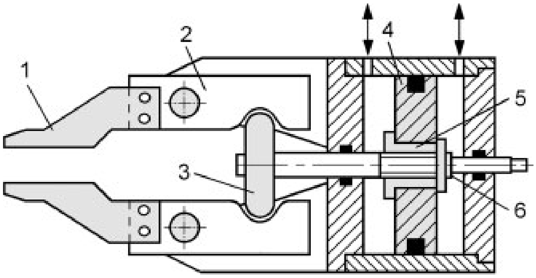


Fig. 3.75: Angular grippers with different elements for force transmission
1 electric motor, 2 return spring, 3 gripper jaw, 4 object, 5 gripper finger, 6 roller, 7 threaded spindle, 8 cone, 9 pneumatic cylinder, 10 base plate, 11 toothed rack, 12 movable semi-prism, 13 fixed semi-prism



1 gripper jaw
2 gripper finger
3 drive disk
4 piston
5 threaded nut
6 adjustment spindle

Fig. 3.76: Gripper with adjustable stroke position

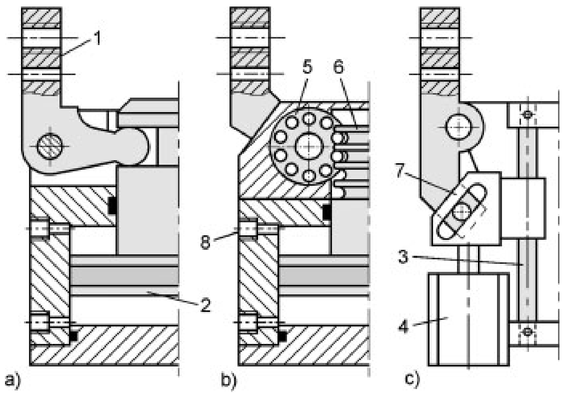
The example shown in Figure 3.76 illustrates one solution for adjustment of the stroke position of the gripper finger in which the piston rod can be adjusted within the piston by means of a thread. It is also possible to attach stop disks (inside and outside) in order to limit, or damp, the travel. The fingers are shown without return springs.

Figure 3.77 shows a selection of commercially available grippers (Fig. 3.77 a and b; *Festo*). Intermediate mechanical links containing more or less gear components transform the piston motion into rotary motion. The forced control of the gripper fingers shown in Figure 3.77 a results in simultaneous and centred motion but the opening angle of 20° for the separate fingers is rather limited.

A somewhat improved situation is achieved by using toothed rack and pinion gears where opening angles as large as 90° can be reached. Their principle ensures that the gripping torque remains constant across the entire opening and closure angle.

Typical lever gears depicted in Figure 3.78 demonstrate gripping forces which can be expected depending on the relevant kinematics.

Figure 3.79 shows a gripper design which combines the advantages of the angular gripper with those of the parallel jaw gripper. The jaw opening angle can be as large as 180°. A parallel motion producing high gripping force complements the jaw motion in the last few millimetres of movement. The closure of this gripper is absolutely centred, with a repeatability of ± 0.02 mm.



1 gripper finger
2 pneumatic piston
3 straight line guide
4 pneumatic cylinder
5 pinion
6 toothed rack
7 cam slide
8 compressed air connection

Fig. 3.77: Various designs of angular grippers
a) angle lever mechanics, b) toothed rack and pinion gear, c) sliding block and wedge gear

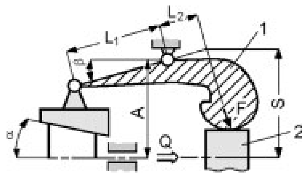
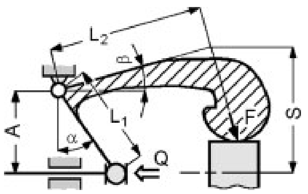
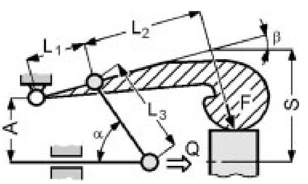
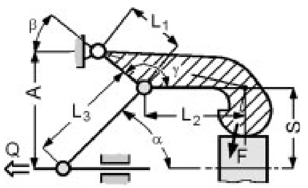
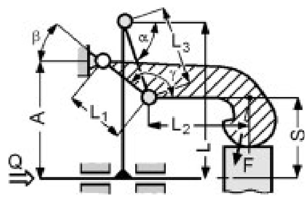
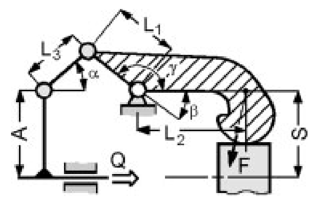
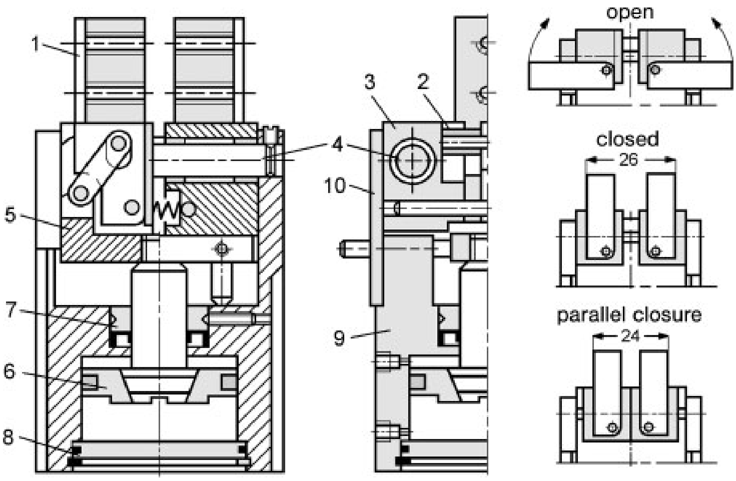
	$F = \frac{Q}{2} \cdot \frac{L_1}{L_2} \cdot \frac{\cos(\alpha + \beta)}{\sin\alpha}$ $S = A + L_2 \cdot \sin\beta$ 1 gripper jaw 2 workpiece
	$F = \frac{Q}{2} \cdot \frac{L_1}{L_2} \cdot \cos\beta$ $S = A + L_2 \cdot \sin\alpha$
	$F = \frac{Q}{2} \cdot \frac{L_1}{L_1 + L_2} \cdot \frac{\sin(\alpha + \beta)}{\cos\alpha}$ $\beta = \arcsin \frac{L_3 \cdot \sin\alpha - A}{L_1}$ $S = A + (L_1 + L_2) \cdot \sin\beta$
	$F = \frac{Q}{2}\left[\frac{L_1 \cdot \sin(\alpha + \beta)}{\sqrt{L_1^2 + L_2^2 - 2 \cdot L_1 \cdot L_2 \cdot \sin\gamma}} - \frac{1}{\cos\alpha}\right]$ $\sin\beta = \frac{L_3 \cdot \sin\alpha - A}{L_1}$ $S = A - L_1 \cdot \sin\beta + L_2 \cdot \sin(\beta + \gamma)$
	$F = \frac{Q}{2}\left[\frac{L_1 \cdot \sin(\alpha + \beta)}{\sqrt{L_1^2 + L_2^2 - 2 \cdot L_1 \cdot L_2 \cdot \cos\gamma}} - \frac{1}{\cos\alpha}\right]$ $\sin\beta = \frac{A - L + L_3 \cdot \sin\alpha}{L_1}$ $S = A - L_2 \cdot \sin\beta + L_2 \cdot \sin(\beta + \gamma)$
	$F = \frac{Q}{2} \cdot \frac{\sin(\alpha + \beta)}{\cos\alpha} \cdot \frac{L_1}{L_2}$ $\sin\beta = \frac{L_3}{L_1} \cdot \sin\alpha$ $S = A + L_2 \cdot \sin(\gamma + \beta)$

Fig. 3.78: Kinematic models of some lever gears whose gripper jaws traverse curved paths



1 gripper jaw
2 curved roller
3 guiding slide
4 guiding shaft
5 slide
6 piston
7 bush
8 O-ring
9 carrier
10 plate

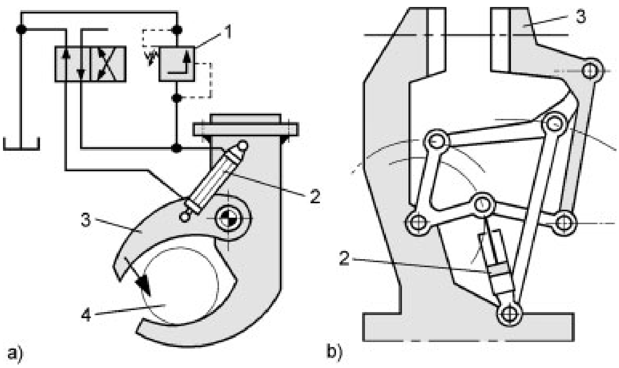
Fig. 3.79: Mechanics of the angular-parallel gripper (*Gemotec* Patent)

The O-ring can be removed from the cylinder and a gripping force securing cylinder (see Fig. 13.51) substituted if desired. The angular-parallel travel is combined within the same functional unit. The toggle lever construction of the transmission lever comes into play only in the last phase of motion.

Numerous designs of angular grippers for various applications exist, e.g. grippers with a single moving finger. Figure 3.80 shows a hydraulic gripper for which only a single pneumatic cylinder is sufficient as prime mover. Standard products, like toggle levers, can be designed for use with most actuators for use in impactive grippers.

The lever mechanics of the gripper depicted in Figure 3.80 b ensures highly repeatable guidance of the moving jaw along a straight line and parallel to the vertical axis.

Simple spring loaded single finger grippers can be used for the handling of relatively light objects as depicted in Figure 3.81. Actuation of the spring loaded mechanism for object prehension may be pneumatic or electromagnetic. Object retention is governed purely by spring force.



1 pressure control valve
2 operating cylinder
3 moving finger
4 workpiece

Fig. 3.80: Angular gripper with one moving finger [3-12]
a) hydraulic gripper
b) six-link gripper gear

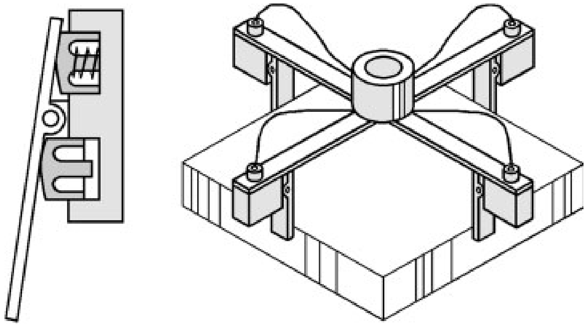


Fig. 3.81: Simple 4 finger gripper for light parts

The prehension of long parts (exceeding 200 mm) may require the combination of several individual grippers as can be seen in Figure 3.82. The use of two grippers halves the load bearing capacity per gripper as long as the object centre of gravity lies precisely midway between the two grippers. However, this does not avoid the problem of the large radius of gyration which the robot experiences. Robot load ratings are normally given by manufacturers as being centred at the tool point. For offset load bearing capacity the user should consult the relevant robot specifications.

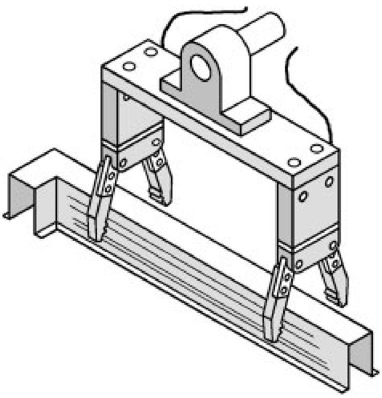
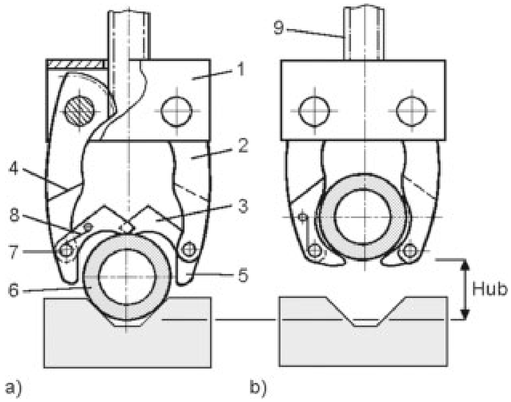


Fig. 3.82: Two point prehension for long workpieces

Finally, there exist many impactive angular grippers with special properties. Figure 3.83 shows as an example a patented gripper which is capable of removing round parts from planar (or indented) surfaces by finger shape matching. This is achieved through spring-mounted jaws (torsion springs) which close about the workpiece as gripping force is applied.

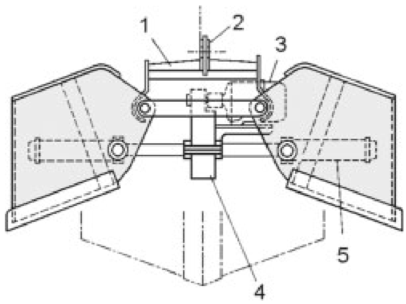
It is interesting to note that the angular mechanisms used in excavators are also occasionally employed in robot grippers for the handling of bulk materials. Almost any geared prime mover may be used and designs are typically as shown in Figure 3.84.

Figure 3.85 shows a gripper with interesting finger kinematics, intended for the handling of 25-kg sacks. The curved toothed rack and pinion gear permits a wide range of fin-



1 gripper housing
2 gripper finger
3 gripper jaw
4 jaw stop
5 holding claw
6 workpiece
7 joint pivot
8 torsion spring
9 toothed rack

Fig. 3.83: Lifting of round parts by spring loaded jaws
a) gripper in pre-prehension position
b) post-prehension (retention)



1 gripper head
2 mounting
3 prime mover
4 gear system
5 closure spindle with protection tube

Fig. 3.84: Shovel gripper (excavator)

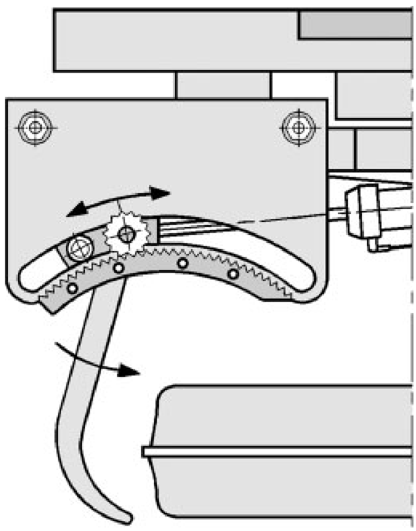


Fig. 3.85: Sack gripper for palletizing tasks (*Roteg*)

ger motion. The sack, to be removed from a pallet or conveyor, is enclosed initially by shape matching of the fingers to the sack topology. In the final motional phase the fingers clamp the sack which may result in a slight degree of compression of the sack but prevents slippage particularly in cases of differing weight or fill level.

There are a number of interesting case studies, dealt with in Chapter 14, dedicated to the prehension and manipulation of sacks and bagged products.

3.2.3
Radial Impactive Grippers (Centring Grippers)

Radial grippers, known also as centrical or self-centring grippers, are mostly three jaw grippers capable of aligning the object along the gripper axis. They are commonly used for the handling of cylindrical workpieces in loading and mounting operations. The grasping organs may close in a straight line or along curved path. Figure 3.86 shows some design examples with various gear configurations.

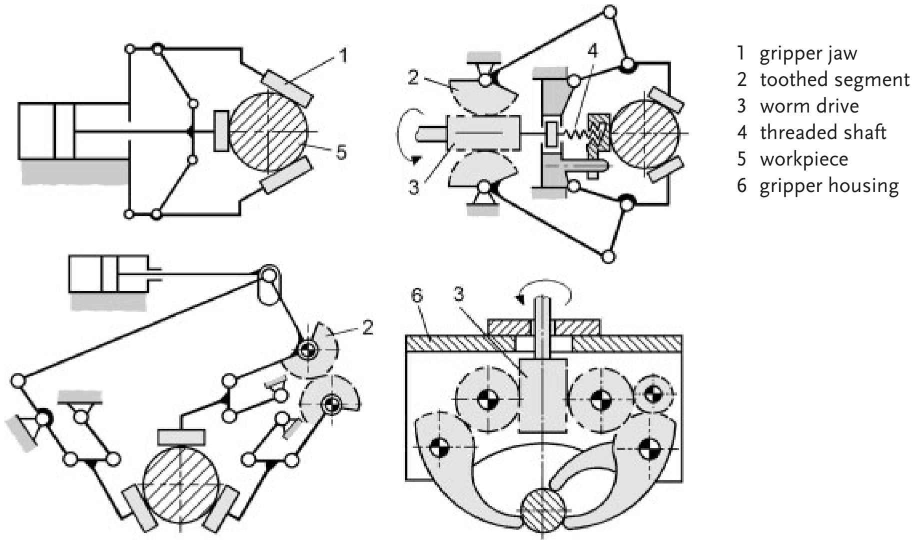


Fig. 3.86: Radial grippers
a) basic model with straight linkages, b) use of worm drive and screw mechanism,
c) linkages with pinion gears, d) pinion gears with intermediate wheel and
reversal of rotation direction for the third gripper finger

Figure 3.87 shows some additional designs where actuation is realized pneumatically by a piston or rotary wing.

A particularly large gripping range can be achieved using the gripper schematically shown in Figure 3.87 c, where the three fingers close along a curved path towards the centre of the gripper. Furthermore, the prehension range can be altered by inserting the gripping pins (fingers) into different holes in the jaws. The pivoting angle of the rotary

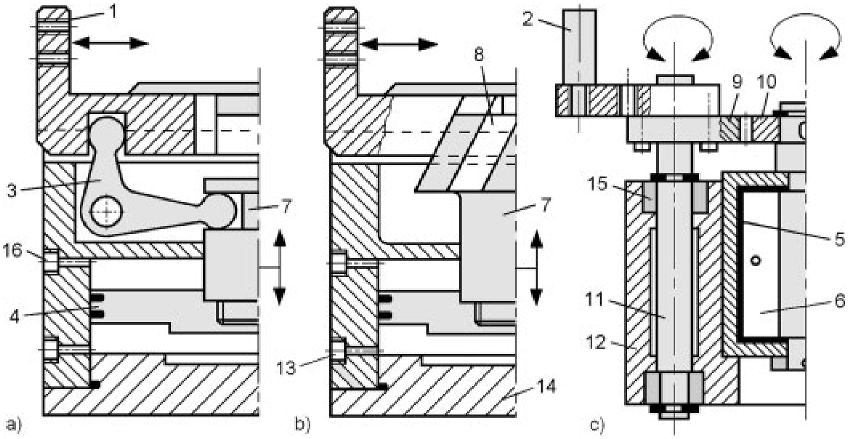


Fig. 3.87: Principle of construction of some radial grippers with three and more fingers
a) angle lever mechanics, b) (simplified) wedge clamp mechanics, c) toothed segment gear
1 gripper basic jaw, 2 gripping pin, 3 angle lever, 4 piston, 5 seal, 6 rotary wing drive,
7 piston rod, 8 wedge clamp gear, 9 segment gear, 10 toothed wheel, 11 gripper finger axis,
12 housing, 13 compressed air connection: open, 14 cylinder cover, 15 bearing bush,
16 compressed air connection: close

wing can be limited at both end positions and the limits varied. No modifications are necessary for application as an internal gripper.

3.2.4 Internal Grippers

Internal grippers, prehend the workpiece from within, normally by impactive means. They are more compact than external grippers and so require less room for manoeuvre – the interference contour of the gripper is small. A pneumatic cylinder causes the fingers to move outward in a direction perpendicular to the axis of actuation. In Figure 3.88 a and b a conical wedge causes horizontal movement of an O-ring or pins. In Figure 3.88 c the components of a tapered sliding link are splayed outward.

Figure 3.89 shows an impactive gripper for internal prehension whereby the prehension force is produced by an electromagnetic solenoid. The mechanical action of the solenoid retracts a conical wedge against a spring steel collet thus spreading the end of the collet within the object to be gripped. The elasticity of the collet also acts as the return spring as the wedge is allowed to drop to facilitate object release. This principle is suitable for the prehension of small light parts, particularly in the absence of a pneumatic supply.

The design shown in Figure 3.90 contains three cross slides in the carrier which move in the direction of impaction as a result of the vertical motion of the central collar stud. The gripper first makes contact with the workpiece before extending the cross slides. Jaw stroke is limited but jaws are normally exchangeable allowing compatibility within a range of sizes.

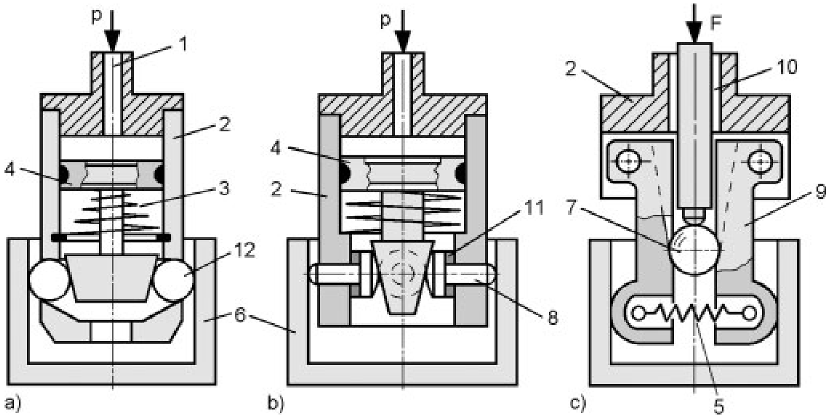
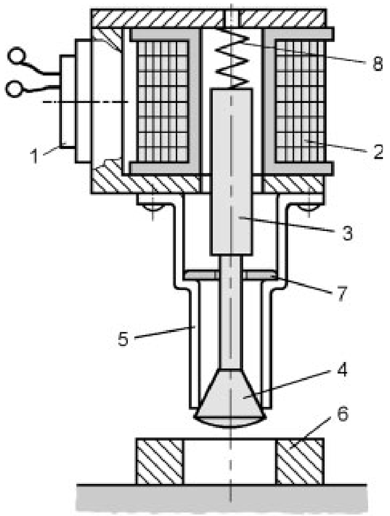


Fig. 3.88: Designs of internal grippers
a) clamping ring, b) clamping pins c) clamping jaws
1 compressed air connection, 2 housing, 3 return spring, 4 piston, 5 tension spring, 6 workpiece, 7 sphere, 8 clamping pin, 9 tapered jawl, 10 guide bush, 11 soft rubber buffer, 12 O-ring

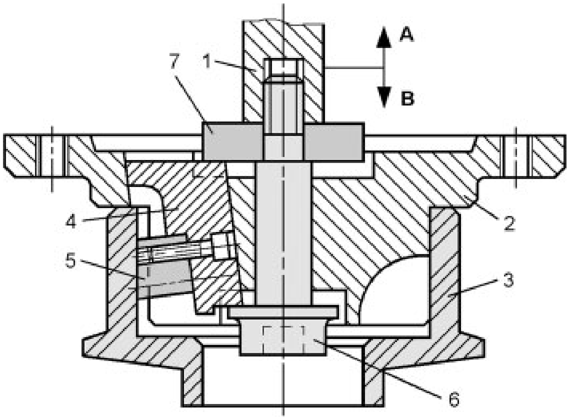


1 flange
2 electromagnet
3 magnetic core
4 conical wedge
5 collet
6 gripped object
7 stop disk
8 return spring

Fig. 3.89: Electromagnetically actuated internal gripper

In the design shown in Figure 3.91 a, insertion of the gripper into the hole or recess in the object to be acquired causes retraction of the pendulum jaw and vertical displacement of the conical wedge. Pneumatic pressure forces the conical wedge downwards and the jaw outwards. On removal of the pneumatic pressure, the return spring forces the wedge upwards thus facilitating object release.

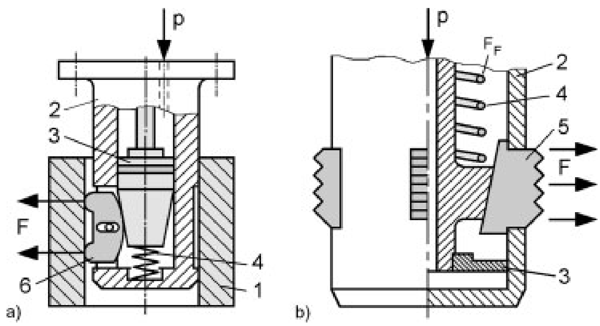
Figure 3.91 b shows a variant which does not rely on a return spring for object release but requires actuation (pneumatic or hydraulic) to terminate retention.



1 mechanical connection from prime mover
2 gripper substrate
3 workpiece
4 cross slide
5 gripper jaw
6 collar stud
7 hardened ring

A movement for prehension
B movement for release

Fig. 3.90: Short stroke internal gripper



1 workpiece
2 mandrel housing
3 piston
4 return spring
5 impactive jaw
6 pendulum jaw

F clamping force
F_F return spring force
p compressed air

Fig. 3.91: Gripping mandrel for internal grip
a) actuated prehension, b) actuated release

For the design shown in Figure 3.91 a the retention force is dependant on the pneumatic pressure while for the version shown in Figure 3.91 b the retention force F is determined solely by the spring force and the wedge slope α. According to Figure 3.92 the wedge effect is given by:

$$F = F_F \cdot \frac{\sin(\alpha + \varrho_2 + \varrho_3) \cdot \cos\varrho_1}{\cos(\alpha + \varrho_1 + \varrho_2) \cdot \cos\varrho_3} \quad (3.37)$$

$$\mu = \tan\varrho \quad (3.38)$$

$(\mu_1 = \tan\varrho_1, \mu_2 = \tan\varrho_2, \mu_3 = \tan\varrho_3)$

μ coefficient of friction
ϱ angle of friction

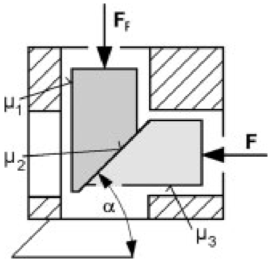


Fig. 3.92: Force transmission with wedge elements

For a symmetrical system with identical angles of friction:

$$F = F_{\mathrm{F}} \cdot \tan(\alpha + 2 \cdot \varrho) \tag{3.39}$$

3.2.5
Gripper with Self-blocking Capability

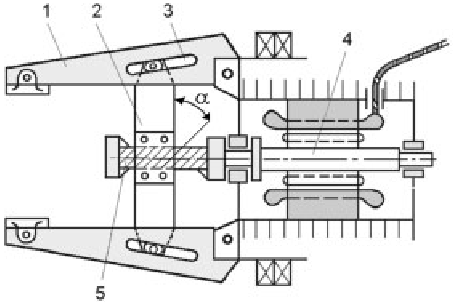
Impactive grippers can be also made to self-block. Self blocking means that the jaws may be locked into the closed condition during motion, for example when subjected to large centrifugal forces tangential to the prehension points. Self-blocking can be passive or active. Many electro-mechanically driven impactive grippers are by their nature self-blocking because the gear ratio and/or the pitch of the drive screw is fine enough that reverse driving is impossible.

Blocking may also be achieved in an active manner as shown in the spindle driven example illustrated in Figure 3.93.

The spindle is protected against reverse rotation when the threaded transfer element is subjected to a force, provided that the lead angle of the thread satisfies the inequality $\alpha \leq \varrho$ where ϱ is determined again by expression 3.38:

$$\mu = \tan \varrho$$

μ spindle – spindle nut coefficient of friction
ϱ angle of friction



1 gripper finger
2 threaded transfer element
3 guide
4 prime mover shaft
5 threaded spindle
α lead angle

Fig. 3.93: Patented angular gripper with electromotive actuation

Coarse spindles with large lead angle α may provide rapid jaw closure but are not self-blocking. In the case of electrical drives, the mechanical blocking provided by such designs may be augmented by maintaining the motor active at reduced current.

Figure 3.94 shows two designs using roller cranks. Attempts to open the closed gripper jaws by applying a force F_G will result in a lever force at the pivot F_H. This force is decomposed into the components F_{HX} and F_{HY} because the driving slide can only move in the direction of the x-axis. Depending on the geometry of the gripper finger, the force F_{HX} can intensify or weaken the closing force. Amplification would block the gripper jaws, i.e. self-blocking takes place. The presented force diagram does not contain either the friction torques, which occur in the lever axis, or any friction forces between the roller and the crank.

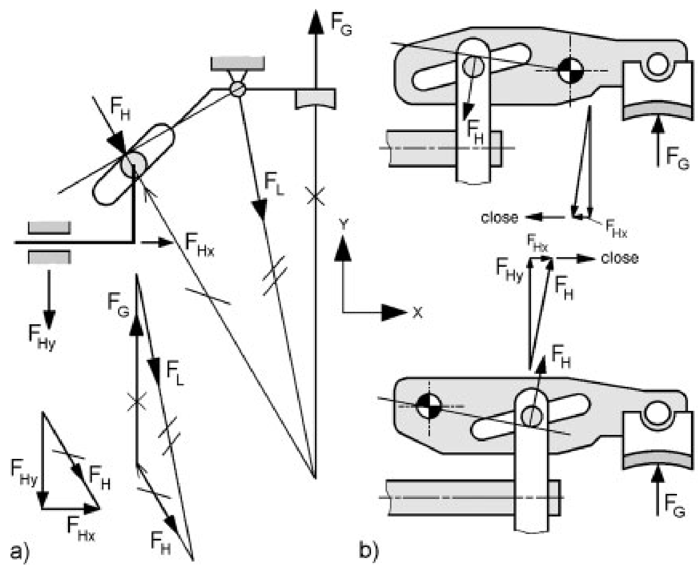
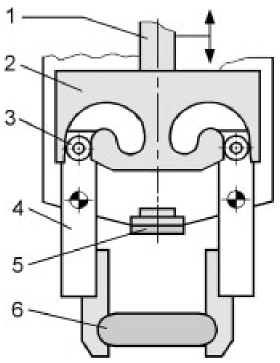


Fig. 3.94: Impactive grippers with roller crank
a) force diagram of self-blocking, b) examples of grippers with self-blocking

Angular grippers often offer advantages in compactness of design, exhibiting only a limited interference contour. The linear translation element, otherwise necessary for the return stroke of the gripper, is superfluous. In order to achieve acceptable closing forces in the final stages of closure toggle-level gears are sometimes necessary. Large grippers allow for good accommodation of robust mechanics. However, when applying this principle to very small grippers with delicate joints, some load bearing capabilities must be sacrificed. For this reason the gripper depicted in Figure 3.95 is provided with a curve guide (roller crank) for the generation of finger motion. The force-displacement diagram can be applied to the curved form in such a way that a large holding force is available towards the end of closure (though without self-blocking). This prevents overload problems otherwise typical for toggle lever gears. The disadvantage is that the gripper jaws must be designed in such a way that they exactly match the size of the workpiece.



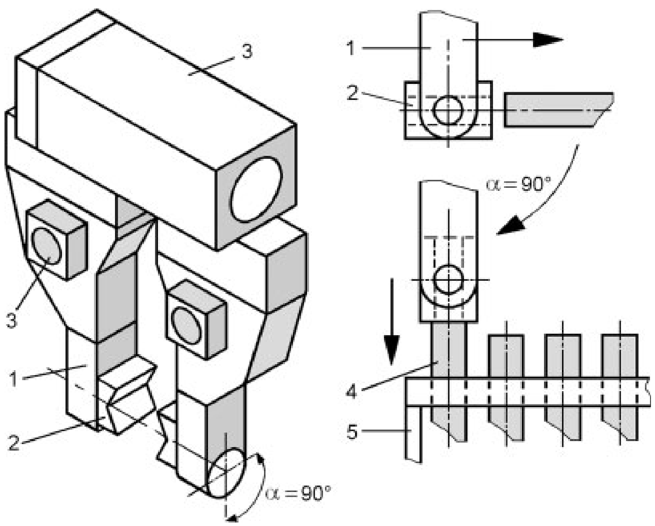
1 mechanical connection from prime mover
2 robust cam segment
3 guide roll
4 gripper jaw
5 adjustable, damped stop
6 workpiece

Fig. 3.95: Angular gripper with roller crank (*Montech*)

3.2.6
Rotatable Jaw Grippers

Occasionally it is necessary to integrate rotation of an object within the gripper during retention to assist manipulation without the necessity of additional hardware. The gripper shown in Figure 3.96 is capable of changing the orientation of the object by $\pm 90°$. The complete rotational mechanics, including the motor, are often integrated into the finger. In most cases it is sufficient for actuation of only one gripper jaw, the opposite one being rotated passively. The pivoting angle end position is adjustable to within $\pm 3°$ and the achievable repeatability amounts to around 0.01°.

The transmission of rotational motion from the prime mover to a pivoted jaw can be realized by toothed belts or wheels. The motor can be allowed to move together with the jaws or it may be secured to the housing and motion transmitted by means of a spline shaft. Figure 3.97 shows several gear solutions.



1 gripper finger
2 gripper jaw
3 pneumatic cylinder
4 workpiece
5 workpiece magazine
α pivoting angle

Fig. 3.96: Rotating gripper

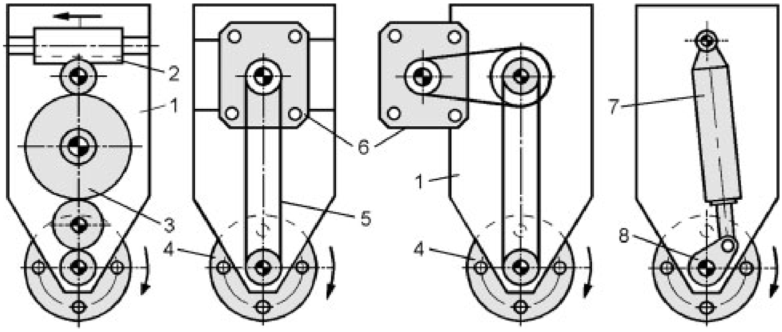


Fig. 3.97: Jaw actuation for rotational grippers
1 finger housing, 2 pneumatic cylinder with toothed cylinder, 3 toothed wheel, 4 rotatable plate for the gripper jaw, 5 toothed belt, 6 motor (electric motor or pneumatic rotary wing unit), 7 pneumatic cylinder, 8 pivot arm

A pivoting angle of 90° or 180° is not always sufficient. The gripper presented in Figure 11.27 (see Chapter 11), e.g., fulfils a different task, rotating the prehended workpiece through any desired angle (usually for inspection and measurement purposes).

3.2.7 Gripper Finger and Jaw Design

The terms finger and jaw are often used interchangeably. Strictly speaking, the jaws are the parts connected to the driving gear mechanism (or prime mover directly) and the fingers are an extension thereto. However, in much of the literature this status is reversed. This is particularly common in the case of small rotatable jaws situated at the end of the fingers.

Gripper fingers (or sometimes the jaws themselves) come into direct contact with the workpiece. This leads to interactions in terms of finger topology, retention reliability, acceptability of tolerances and the necessary number of grasping organs. The gripper design can be further influenced by process-related requirements, such as the necessary joining forces in an assembly process.

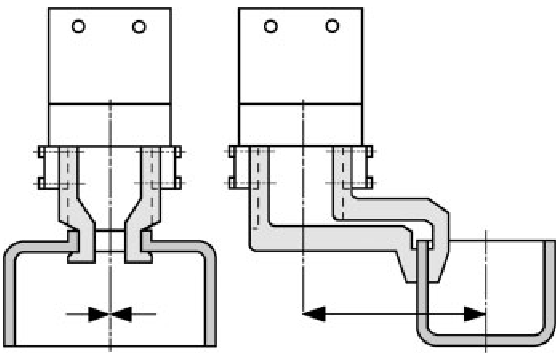


Fig. 3.98: Gripper jaw shapes for internal and combined grips

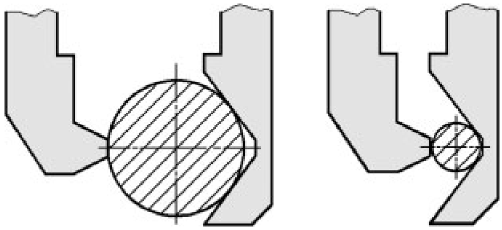
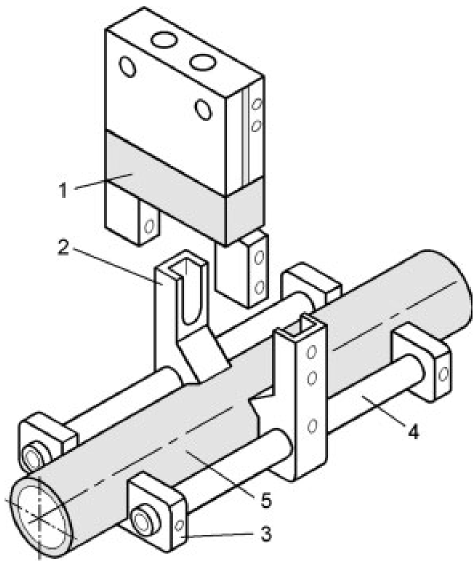


Fig. 3.99: Jaw design for round parts with a large diameter range

Figure 3.98 shows two jaw and finger shapes respectively, for impactive prehension. The curved fingers are chosen in the presented example for process related reasons.

The choice of finger design can also influence the ability to accommodate a mechanically large range of object diameters, as illustrated in Figure 3.99. The jaws are formed in such a way that a reliable three-point retention of even very small objects is possible.

Extended jaw supports may be necessary for the prehension of long parts as demonstrated in Figure 3.100. The solution shown is of particular importance in cases where the prehension centre does not coincide with the workpiece mass centre and unwanted tilt moments act on the gripper fingers exerting pressure on the gripper jaws.



1 parallel jaw gripper
2 gripper jaw
3 supporting element
4 tube
5 workpiece

Fig. 3.100: Extended jaw supports

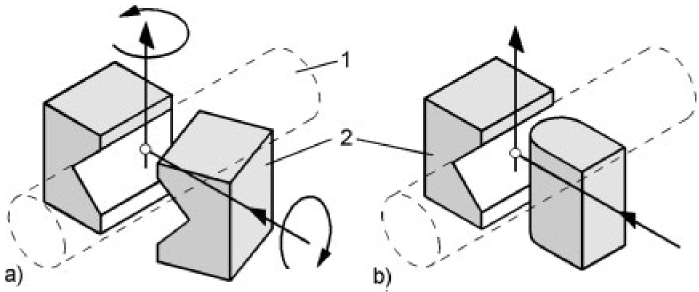
The matching of object and gripper contact points should be statically determined in terms of an unambiguous position of the object with respect to the gripper. The degree of the matching over determination $\ddot{u}$ can be calculated from expression (3.38):

$$\ddot{u} = f + 6\,(k - 1) - \sum_{i=1}^{k} f_1 \tag{3.38}$$

The degree of over determination indicates the number of elementary motions necessary for a statically defined object retention whereby the parameters in equation (3.38) are:

f joint degrees of freedom which the matching should possess
k number of sub-joints
f_i degree of freedom of the i-th sub-joint of the k sub-joints into which the matching can be decomposed

Figure 3.101 shows two examples for this.



1 cylindrical object
2 gripper fingers

Fig. 3.101: Matching of fingers and object
a) prismatic fingers, b) combination of prism and rounded bar

In the example presented in Figure 3.101 a the shaft and the gripper prisms form a rotation-translation joint with $f = 2$ which can be decomposed into $k = 4$ cylinder slab joints as sub-joints each with $f_i = 4$ (2 rotations, 2 translations). From which it follows that:

$$\ddot{u} = 2 + 6\,(4 - 1) - (4 + 4 + 4 + 4) = 4$$

This means that three additional elementary motions are required for static determination of the matching in addition to the translational motion of the grasping organs relative to each other. They can be realized, e.g., by a ball joint between one of the gripper fingers and its jaw pivot.

The matching of object to finger profile shown in Figure 3.101 b consists of 2 cylinder slab joints and one cylinder-cylinder joint with $f_3 = 1$. In this case $\ddot{u} = 2 + 6(3 - 1) - (4 + 4 + 5) = 1$ and the matching is statically defined. Although a point contact takes place, for correct shaping of the finger, i.e., for favourable lubrication, this does not necessarily lead to an unacceptable level of surface pressure.

The term over *determination* should not be confused with *dependency*. Dependencies result from position deviations between the object and fingers. Since such deviations occur rather often when positioning the gripper relative to the object or when positioning the object relative to its final receiver (e.g. a chuck), it is impossible to avoid additional movements. The number of these movements along and about the axes of the reference coordinate system corresponds to the missing degrees of freedom, i.e. the dependencies u of the kinematic chain comprising the receiver, the object, and the finger which make contact with (but do not secure) the object. It is necessary that the dependancy

$$u = b - F \tag{3.39}$$

where

$$F = b \cdot (n - 1) - b \cdot g + \left(\sum^{g} f\right) - f_{id} \tag{3.40}$$

F degree of freedom of the kinematic chain
b for a spatial chain $b = 6$
f joint degree of freedom
f_{id} identical joint degree of freedom
g number of joints
n number of links

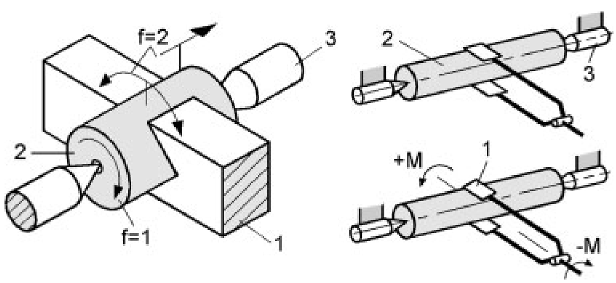
From equations (3.39) and (3.40) one obtains the equation for the number of dependencies.

$$u = b \cdot (2 - n + g) - \left(\sum^{g} f\right) - f_{id} \tag{3.41}$$

Figure 3.102 demonstrates a simple example of gripping a shaft which, being fixed between two tips, can still move with a joint degree of freedom $f = 1$ relative to the reference frame. The possible rotational-translational motion between the gripper jaws and the shaft has $f = 2$ whereas the rotation occurs as an identical degree of freedom, i.e. $f_{id} = 1$. There exist $n = 3$ links and $g = 2$ joints. For the number of dependencies u this gives:

$$u = 6\,(2 - 3 + 2) - (1 + 2) + 1 = 4$$

The meaning of the above is: In order to avoid overstraining as a consequence of missing degrees of freedom, certain gripper links must be flexible. To this aim, self-adjusting compensation units between the gripper and the robot flange are often included. This leads to automatic compensation of deviations from the workpiece axis from its theoretically correct position during prehension operations.



1 gripper jaw
2 object
3 tip stabilising

M torque

Fig. 3.102: Dependencies during shaft prehension

3.2.8
Self Securing Grippers

Self securing grippers retain the object purely by force matching. The grippers which will be presented in this section produce the retention force by spring or mass effects.

3.2.8.1
Securing Through Spring Forces

Spring loaded grippers present the simplest form of mechanical impactive prehension technology. Firm prehension is determined by contact with the object as demonstrated in Fig. 3.103. For a vertical motion of the gripper, the gripping force F_G can be calculated from (3.42)

$$F_G = \frac{F_F \cdot \alpha}{b} \tag{3.42}$$

F_F spring force
a, b lever dimensions

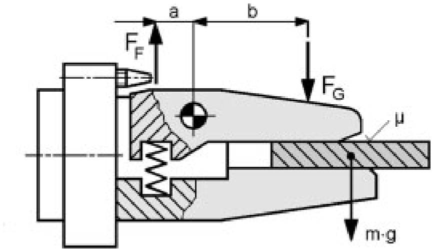
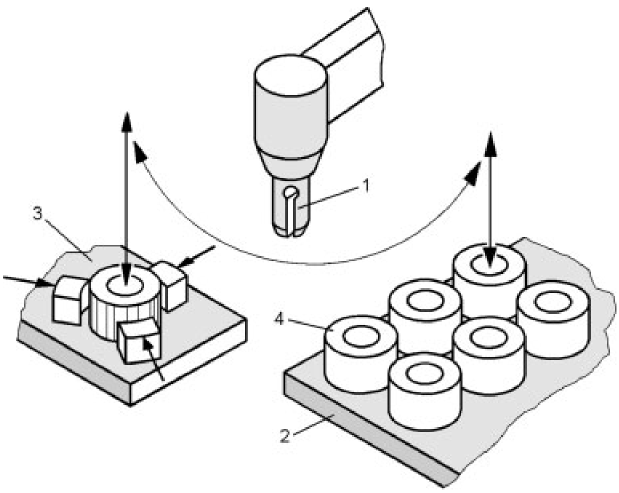
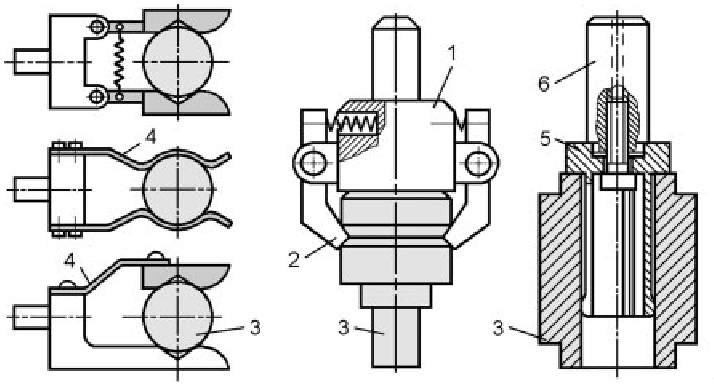


Fig. 3.103: Principle of the spring clamp



1 spring loaded gripper
2 supply magazine
3 clamping device
4 workpiece

Fig. 3.104: Prehension using a spring loaded device



1 carrier
2 stop lever
3 workpiece
4 spring
5 external jaws
6 clamping pivot

Fig. 3.105: Spring clamping gripper

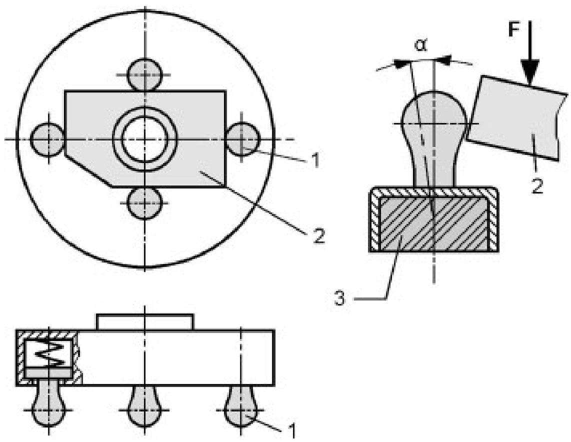
For a 90° clockwise rotation and a vertical translation at relatively low speed, the required spring force F_F (without safety margin) is obtained from (3.43)

$$F_F \geq \frac{m \cdot g \cdot b}{\mu \cdot 2 \cdot \alpha} \qquad (3.43)$$

One drawback of this simplified gripper is that no release mechanics are included. The gripper can only be withdrawn if the object is secured at its destination by additional mechanisms as illustrated in the example in Fig. 3.104.

Some additional grippers which use the same principle are shown in Figure 3.105. None of them possesses its own mechanical actuator.

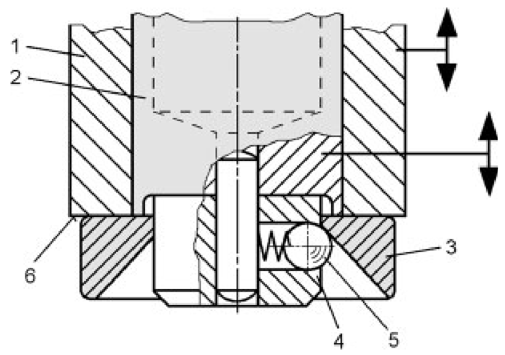
A simple gripper can be designed using lateral pressure clips. A pear-shaped peg is spring mounted in its base and can be deflected by an angle α. The clamping travel is short. Depending on the size of the installation and its components a spring force of 10 to 300 N (Fig. 3.106) is sufficient. The gripper is pressed onto the object to be prehended and controlled release is only possible at the final destination.



1 lateral peg
2 workpiece
3 rubber roll or helical spring

F pressing force
α maximum possible deflection angle

Fig. 3.106: Impactive gripper with lateral pressure pegs



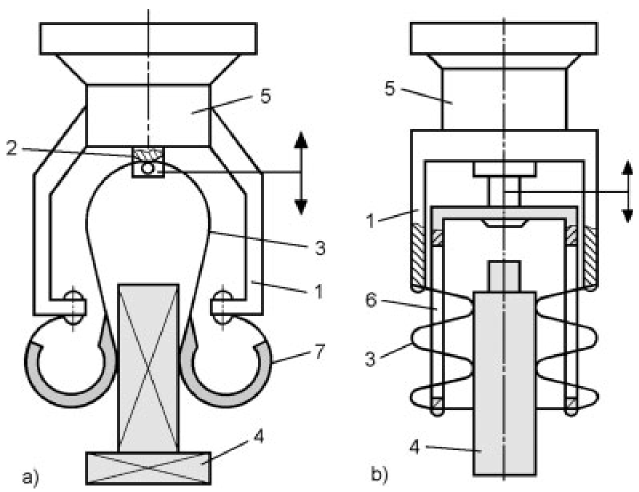
1 collar
2 gripper substrate
3 workpiece
4 flanged rim
5 sphere
6 area of contact

Fig. 3.107: Prehension through a spring loaded sphere

Spring loaded impactive grippers like the one shown in Figure 3.107 contain a roller bearing ring in which a spring loaded sphere sits. A cylindrical collar retracts on contact with the object allowing the spring loaded sphere to extend to the end of its travel within the flanged rim. The protrusion of the sphere under the surface of the object thus affects centred prehension. Ejection of the object can be achieved by moving the collar downwards thereby forcing the sphere back into the recess behind the flanged rim.

Band or leaf springs acting as gripper jaws also provide a degree of conformation to the object geometry. The developed prehension forces are not particularly large and the stroke may be augmented by combination with a linear drive. Lifetime and precision are limited due to the material joint which is subjected to mechanical stress during each gripping stroke. Figure 3.108 shows two examples.

Further gripper designs which may be of interest, mainly intended for special solutions, are illustrated in Figure 3.109. The gripper shown in Figure 3.109 a grasps using elastic fingers and tubes with elliptical cross sections (see also Fig 8.28).



1 housing
2 retractable rod
3 flexible band
4 workpiece
5 drive
6 band spring guide
7 reinforcement

Fig. 3.108: Spring retention gripper
a) band spring loop (Russian Patent 571369), b) band spring meander

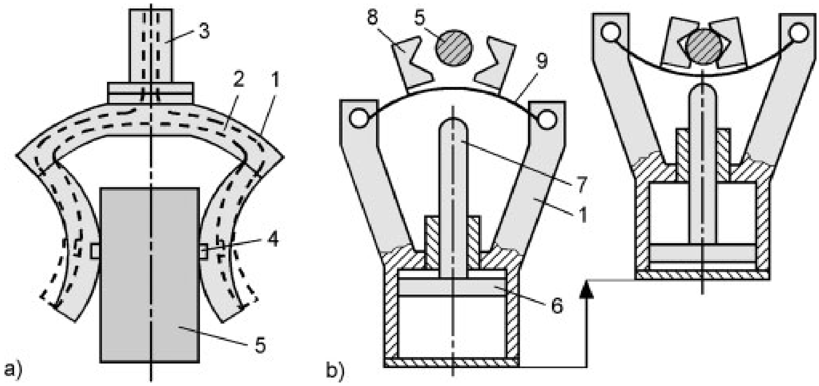
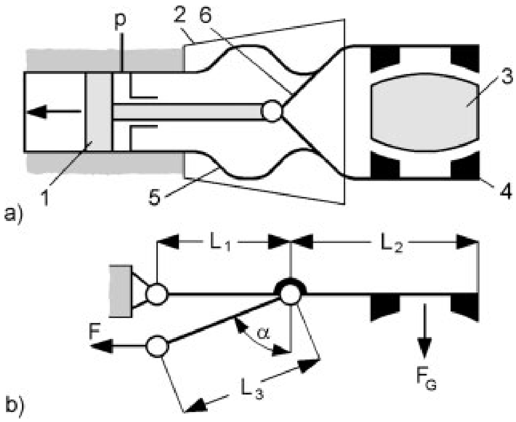


Fig. 3.109: Grippers using spring elements
a) elastic finger gripper, b) leaf spring gripper
1 gripper body, 2 channel for compressed air, 3 gripper connection, 4 nozzle, 5 workpiece, 6 pneumatic cylinder, 7 retractable release rod, 8 gripper jaw, 9 leaf spring

The tubular fingers in the version shown in Figure 3.109 a are hollow and act in the same way as the bending of a *Bourdon* tube in pressure gauges. The gripper shown in Figure 3.109 b is based on the snap principle used in toggle switches and bimetal over-temperature switches. The gripper jaws are fixed to flat springs the ends of which are connected to the gripper housing. If the outward curved spring is pressed to the workpiece to be acquired the spring rapidly overcomes the dead zone and the gripper jaws close with a "snap". In order to release the part, the flat spring must be returned to its initial position by the action of a pneumatic cylinder.

Figure 3.110 shows another gripper with flat spring fingers suitable for the prehension of light parts.



1 pneumatic cylinder
2 housing
3 workpiece
4 gripper jaw
5 flat spring fingers
6 tie

p compressed air

Fig. 3.110: Impactive prehension using flat spring finger
a) kinematic scheme
b) force diagram

An actuator (pneumatic cylinder or solenoid) is required for the closing motion of the gripper jaws. Opening takes place through the spring force alone. The ties must be secured at some appropriate point on the spring finger.

3.2.8.2
Securing Through Object Mass

The astute redirection of gravitational forces on an objects mass into gripping forces is a form of impactive prehension which does not rely on external drives. The generated prehension force is, of course, object mass dependent. Such grippers are used primarily in lifting tools and manually controlled manipulators. Their construction is mechanically simple and a very early version dating from the 19th century is known as the “devil's claw”. These grippers are often used for the manipulation of bar stock, shafts, wood, cases, barrels, tubes and bundled rods. The jaw is opened on release with the help of a spring. Figure 3.111 shows three examples of such grippers.

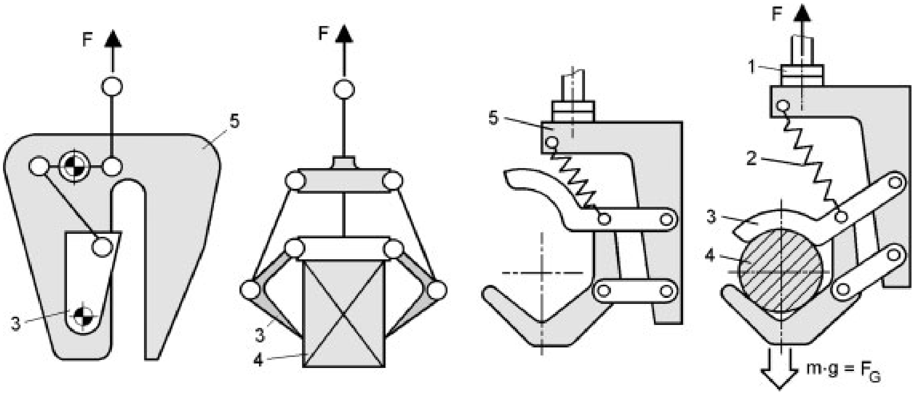
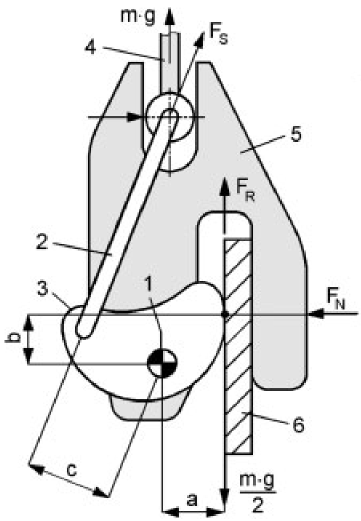


Fig. 3.111: Self sustaining impactive grippers
1 swivel joint, 2 tension spring, 3 gripper jaw, 4 object, 5 baseplate
F lifting force, *m* mass, *g* gravitational acceleration, F_G force due to object mass

These grippers are simple, robust and suitable for outdoor use, for example in transport and logistics industries. There is no theoretical limit to the load capacity because the resulting downward force is proportional to the mass of the object. In practice, the load capacity is of course limited by the allowable mechanical stresses applied to the materials used to build the gripper. On release the jaws are usually opened by integrated tension springs.

A prehension clamp in its simplest form is shown in Figure 3.112. The acquired object, for example a flat plate, is clamped between the gripper jaws through the force $m \cdot g$ and the friction force F_R. Considering the forces acting in this case in more detail:



1 latch centre of rotation
2 retraction rod
3 latch (eccentric clamp)
4 harness
5 carrier
6 prehended object

Fig. 3.112: Gripping clamp for vertical steel plate transportation with mass dependent prehension force

The following relationships hold for the mechanics of the clamp:

$$F_N \cdot b - \frac{m \cdot g}{2} \cdot a - F_s \cdot c = 0 \tag{3.44}$$

$$F_N = \frac{F_s \cdot c + \frac{m \cdot g}{2} \cdot a}{b} \tag{3.45}$$

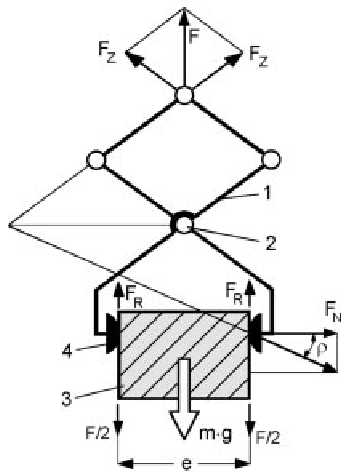
$$F_R = F_N \cdot \mu = 0.5 \cdot m \cdot g \tag{3.46}$$

whereby:
F_N normal force
F_s rod force
F_R friction force
μ friction coefficient workpiece – latch ($\mu \approx 0.35$)

Fig. 3.113 depicts a pivoted impactive gripper which uses leverage. The downward force F_N of the gripper jaws depends on the opening width e between the jaws. Reliable gripping is possible only if the inequality 3.47 is fulfilled:

$$F_N \geq \frac{m \cdot g}{2 \cdot \tan \varrho} \tag{3.47}$$

ϱ angle of friction ($\mu = \tan \varrho$)
F_R frictional force
F_N normal force



1 lever mechanics
2 joint
3 workpiece
4 gripper jaw

F force due to mass
F_R force due to friction
F_N gripping, normal, or holding force

Fig. 3.113: Forces acting through leverage

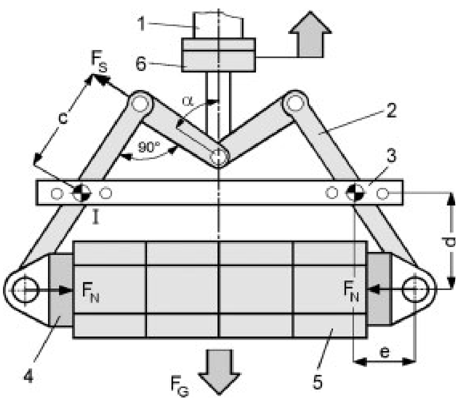
If several parts are simultaneously held by such a gripper as shown in Figure 3.114, the surface pressure must be high enough to ensure reliable prehension without damage to the object.

The prehension force F_N is obtained from the torques acting at the reference point I for which equation 3.48 holds:

$$-F_s \cdot c + F_N \cdot d + \frac{F_G \cdot e}{2} = 0 \tag{3.48}$$

The rod force F_S is given by

$$F_s = \frac{F_G}{2 \cdot \cos \alpha} \tag{3.49}$$



1 retraction rod
2 jaw lever
3 cross bar
4 gripper jaw
5 objects (four blocks in the example)
6 gripper axis of rotation

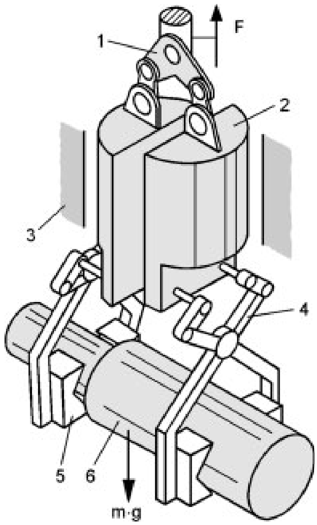
Fig. 3.114: Prehension through leverage

The minimum allowable value for the coefficient of friction μ between the gripper jaw and the object can be calculated from equation 3.50.

$$\mu = \frac{F_G}{2 \cdot F_N} \tag{3.50}$$

F_G force due to mass
α lever position angle
c, d, e geometrical dimensions

Occasionally the prehension of an object at two or more points with differing thicknesses or diameters is necessary. In such circumstances the forces must be as equally distributed between the four contact points as possible. This can be realized using a double impactive gripper of the form shown in Figure 3.115. Initially the larger diameter of the object will cause complete closure of the right hand gripper jaws. The second pair of jaws will continue to close until the smaller diameter is fully enclosed. Balancing of the two grippers is achieved without external control by the purely mechanical action of a pendulum bridge.



1 pendulum bridge
2 displacement
3 straight-line guide
4 scissor mechanism
5 gripper jaw
6 workpiece

$m{\cdot}g$ force due to object mass
F lifting force

Fig. 3.115: Principle of the double impactive gripper with mechanical self-adjustment

Grippers may also be designed to possess locking mechanisms which maintain the gripper jaws open on completion of the object release process and subsequent withdrawal of the gripper. The interlock is automatically offset when the next object is attached. Figure 3.116 shows an example with locking and unlocking.

Figure 3.117 shows a gripper designed for internal prehension. Its main novelty lies in a rhomboid mechanism which is connected to a gripper flange by means of a slide and lever combination. Insertion into the workpiece, e.g. a tube section, is necessary for achieving prehension. Jaw closure takes place automatically as a result of the gravitational forces

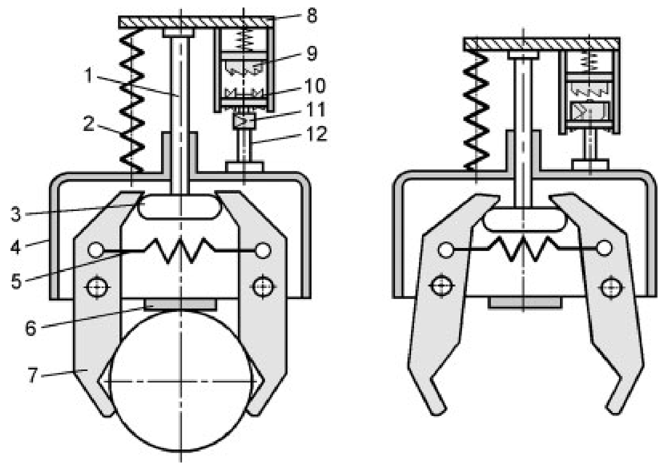


Fig. 3.116: Impactive gripper with automatic control
1 rod, 2 return spring, 3 mushroom head, 4 collar with feedthrough, 5 tension spring, 6 buffered stop, 7 gripper finger, 8 mounting plate, 9 upper jack, 10 lower jack, 11 triangular toothing with latch, 12 rod

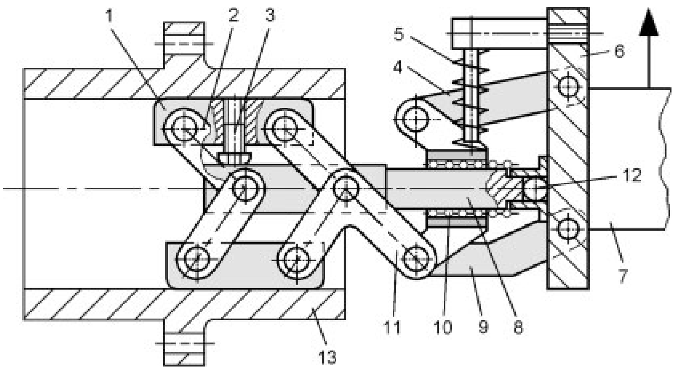
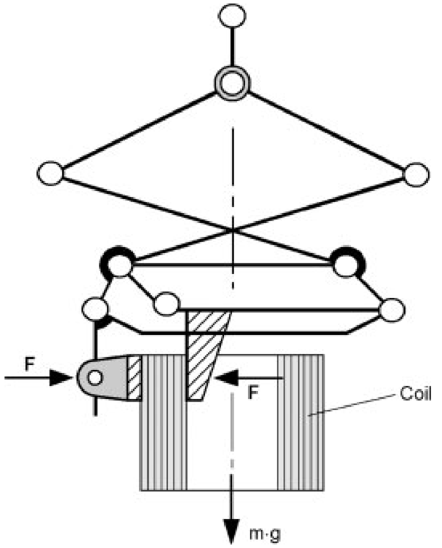


Fig. 3.117: Impactive gripper for internal prehension (B 25 J 15/00, Japanese Patent 53-23584)
1 impactive jaw, 2 jaw lever, 3 setscrew, 4 upper lever, 5 tension spring, 6 flange, 7 robot arm, 8 bearing axis, 9 lower lever, 10 slide and roller bearing, 11 angled lever, 12 sphere, 13 object

when lifting the object. At the same time the bearing axis is connected to the joining flange over a sphere. The flange moves slightly downwards during lifting thus shifting the slide. Object release is achieved by reopening the jaws by the energy stored in the tension spring.

The basic lever design of an impactive mechanism intended for the handling of solenoids is shown in Figure 3.118. Closure of the jaws is realized by virtue of the load over the lever system (typical load ratios can be between 4 : 1 and 6 : 1) while retention relies on frictional forces between object and gripper jaws. An automatic mechanical step switch



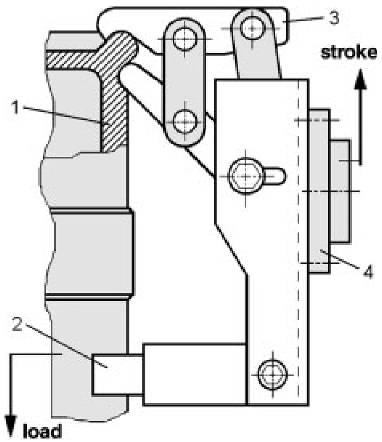
m·g gravitational force on load
F impactive

Fig. 3.118: Principle of internal gripper (*Pfeifer*)

mechanism (not shown in the figure) ensures that opening and closing alternate without the necessity of additional control actions during lifting and release.

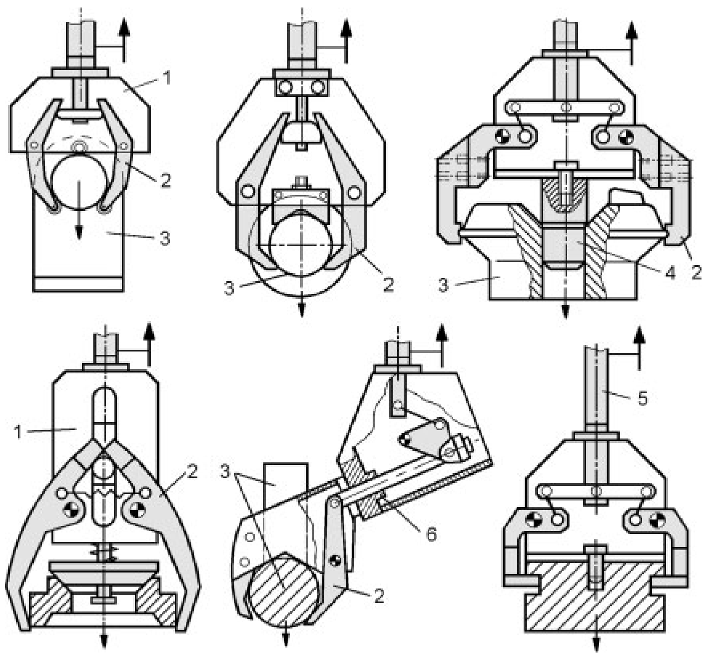
The barrel edge gripper depicted in Figure 3.119 is one of many designs which employ simple lever mechanics for the prehension of sheet metal barrels with ring collars. Both the supporting arm and the opened claw make contact with the barrel on approach, seizing the barrel edge on lifting. The jaws are automatically opened with deposition of the object.

A selection of additional examples of impactive grippers which rely on the mass of the object for prehension and retention are shown in Figure 3.120. Many of these designs are more commonly found in hand-operated manipulators.



1 barrel
2 supporting bracket
3 leverwork
4 mounting flange

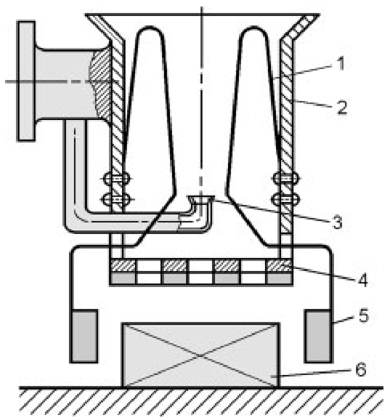
Fig. 3.119: Barrel edge gripper (*P & D Systemtechnik*)



1 gripper carrier
2 gripper finger
3 workpiece
4 centring spigot
5 lifting unit
6 straight line guide

Fig. 3.120: Gripping of machine components with uncontrolled gearfree grippers (*Kahlman*)

For the gripper design shown in Figure 3.121 prehension of the object proceeds indirectly. The escaping air produces an underpressure between the leaf springs, so that the gripper jaws close to secure the workpiece. In addition, a suction effect occurs at the hole plate which maintains retention. The prehension forces produced, are however, rather small. In principle the air flow grippers have extremely simple construction and contain few moving components.

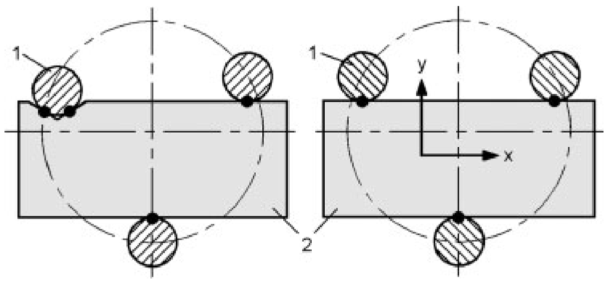


1 leaf spring
2 gripper housing
3 nozzle
4 hole plate
5 gripper jaw
6 gripped object

Fig. 3.121: Impactive gripper with air flow actuation

3.2.9
Three-finger Grippers

Three fingers offer good centring possibilities for the adjustment of the workpiece on the gripper axis which is difficult to realize with astrictive systems. In most cases the kinematically ideal gripping solution for three-point prehension is when the lines of impactive force intersect at one common point. This is easy to achieve for workpieces with axial symmetry but somewhat more difficult for prismatic workpieces.

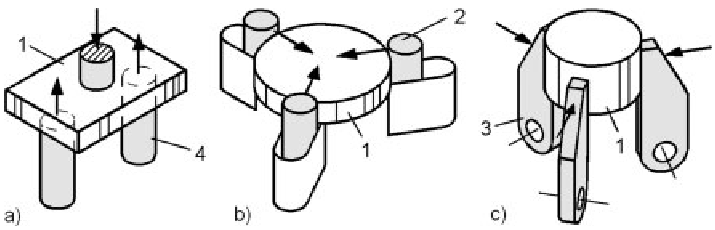


1 gripper finger
2 workpiece

Fig. 3.122: Gripping points for a prismatic workpiece
a) four-point grip
b) three-point grip

For a four-point contact (Fig. 3.122 a) the prehension forces act in two axial directions. Unfortunately not every workpiece can be handled in this manner and an alternative is the three-point contact as shown in Figure 3.122 b, in which case the centring effect in the x-direction is absent.

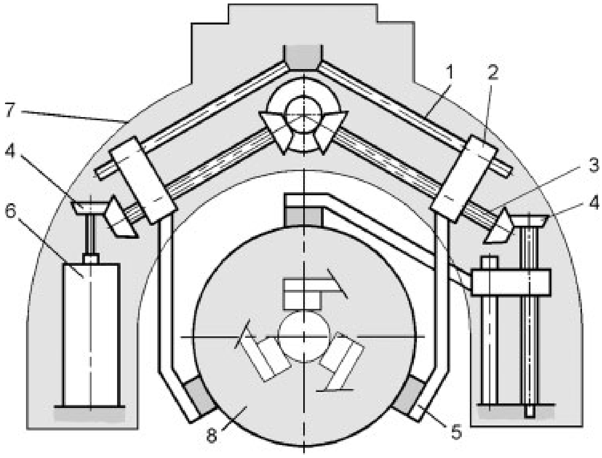
There exist numerous designs for grippers with three fingers. As illustrated in Figure 3.123 the fingers can move together or independently of one another. They can move along a curved path or along a straight line towards the centre.



1 workpiece
2 slide finger
3 pivot finger
4 clamp bolt

Fig. 3.123: Access possibilities for a three-finger gripper
a) claw grip, b) centring sliding fingers, c) centring pivoted fingers

The following Figures illustrate the design principles of a range of three-finger grippers. Figure 3.124 shows a 3-finger gripper with fingers arranged at an angle of 120° capable of a relatively large gripping range. The fingers are driven by an electric motor via a nut-spindle and bevel gear which ensures the correct direction of rotation.



1 straight line guide
2 spindle nut
3 spindle
4 bevel gear
5 gripper finger
6 electric motor
7 base plate
8 workpiece

Fig. 3.124: Three-finger gripper with spindle gear (after *Yamatake Honey-well*)

The grippers shown in Figure 3.125 must be placed over the object to be acquired because a lateral approach is impossible. In both cases the driving motion is transmitted over a ring to which the fingers are mechanically coupled. The fingers may close along a straight line or a curved path. The grippers are well suited for assembly operations with cylindrically shaped objects

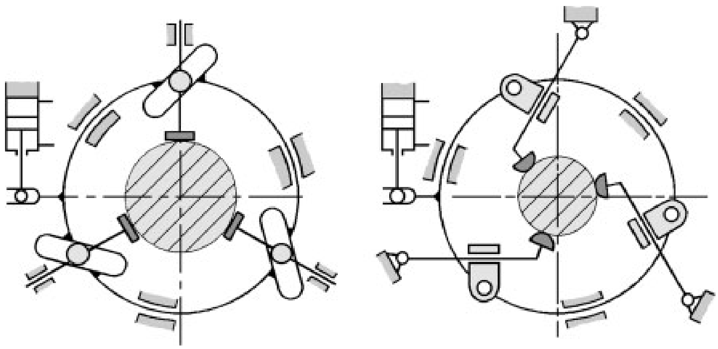


Fig. 3.125: Examples of gears concepts for three-finger grippers

Sometimes steel cables (push-pull cables) are used for the transmission of driving motion to the gripper fingers. This can be a useful and simple solution in the case of large object diameters, especially where the gripper fingers are located some distance from the prime mover (for example, the mounting of toothed wheels on long gear shafts or magazine mandrels). For the concept shown in Figure 3.126 a the fingers close along a curved path. The closing motion is produced by a pneumatic cylinder while the opening is realized by a release spring. In the alternative case, depicted in Figure 3.126 b, the finger motion proceeds along a straight line towards the prehension centre. This is realized by turning a ring with tilted slots in the manner depicted in Figure 3.125 (left). Opening takes place by means of force transmission along a steel cable.

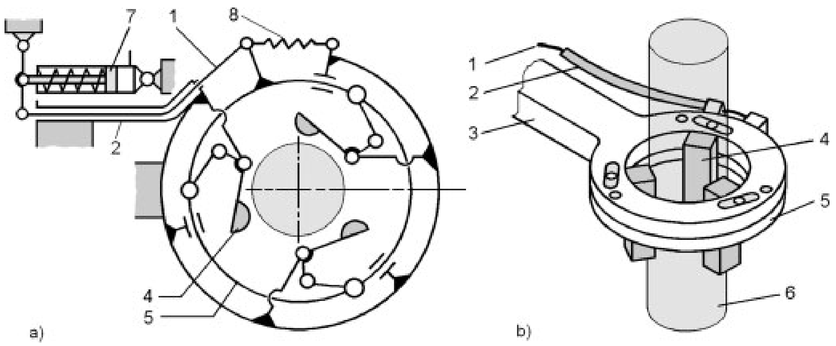
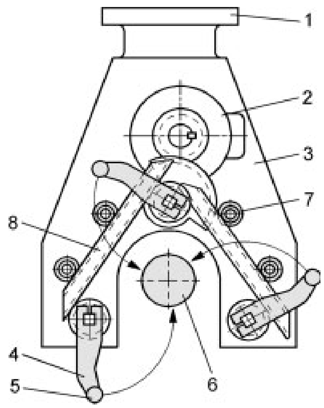


Fig. 3.126: Actuation of gripper fingers with the help of a steel cables
a) kinematic example, b) gripper design
1 steel rope, 2 cladding, 3 gripper carrier, 4 gripper finger, 5 rotary ring, 6 workpiece,
7 pneumatic cylinder, 8 return spring

The 3-finger gripper shown in Figure 3.127 exerts a centring effect on the cylindrical object. The fingers are actuated and synchronised via a rack and pinion mechanism. With its rather wide range of pivoting the gripper is capable of operating over large variations in object diameter.



1 gripper flange
2 motor
3 gripper housing
4 gripper finger
5 exchangeable gripper jaws
6 workpiece
7 supporting roller
8 toothed rack

Fig. 3.127: Three-finger centring gripper

The fingers of the gripper shown in Figure 3.128 are moved by rollers acting against a wedge. The wedge segment must be linearly translated, e.g. by a pneumatic cylinder or an electromechanical drive.

One rather good example of the centring effect achievable with a three-finger angle gripper is shown in Figure 3.129. As with many other angle grippers, the fingers are pivoted to move backwards. Consequently, it is possible to load clamping fixtures without axial translations. The angle clamping unit may open only after prehension has been achieved, i.e. the gripper is occupied. The cup-shaped gripper jaws produce lower surface pressure in comparison to prismatic jaw grippers. This can be an important selection criterion especially when handling thin-walled, delicate or brittle workpieces.

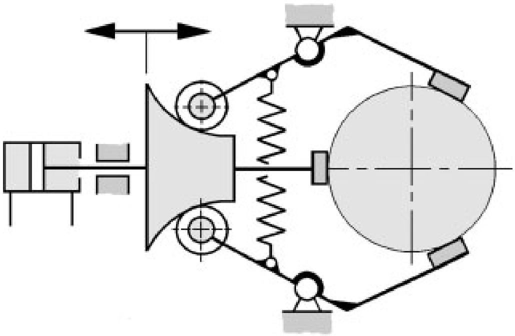
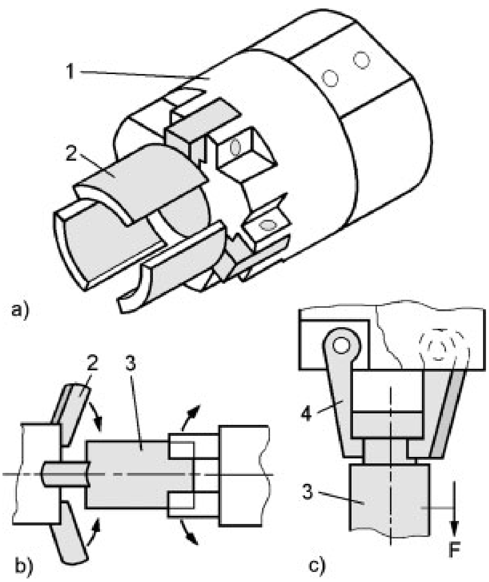


Fig. 3.128: Three-finger gripper using wedge

The inclusion of catches at the end of the gripper jaws makes for better retention of objects containing ring grooves (Fig. 3.129 c). Prehension of the object can be achieved through shape mating rather than relying on gripper force alone. This also has the advantage of more uniform force distribution among the three prehension points.

Astute design of the gripper fingers allows for a certain degree of adaptation to varying workpiece sizes and shapes. Some examples are illustrated in Figure 3.130. Careful attention to individual finger design makes it is possible to acquire long parts (Fig. 3.130 b), though in such cases the axes of the gripper and the object do not necessarily coincide.

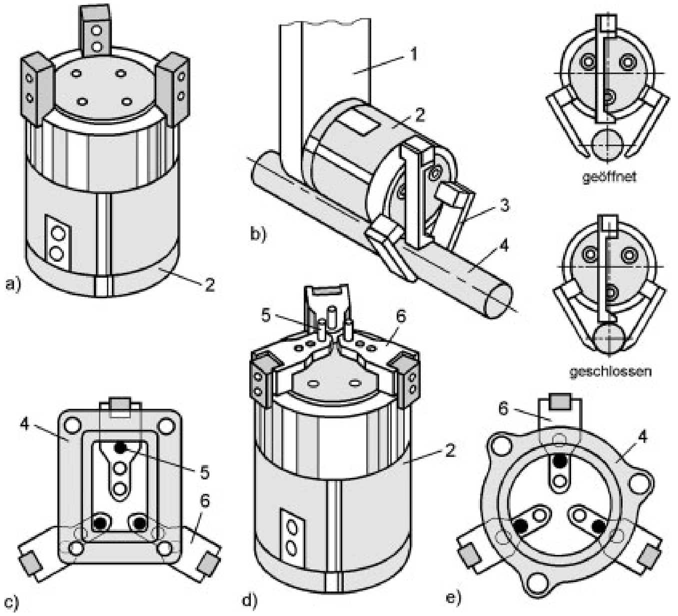
The hardened gripping pins in Figure 3.130 c–e are intended for internal prehension. A choice of mounting holes in the gripper jaws provides a degree of conformability to the profile of the object, though any adjustments must be carried out manually. The pins



1 base gripper
2 cup-shaped gripper jaw
3 workpiece
4 clasp jaw

F joining force exerted by the gripper

Fig. 3.129: Pneumatic three-finger angle gripper
a) design example
b) delivery sequence
c) application in mounting



1 robot arm
2 three-finger gripper
3 special gripper jaw
4 workpiece
5 gripping pin
6 gripper jaw

Fig. 3.130: Modification of the standard three-finger gripper by special finger design a) basic gripper, b) gripper jaw for eccentric grip, c) nonconcentric internal gripping of a housing, d) displaceable pins for variable prehension, e) concentric internal gripping of a flange ring.

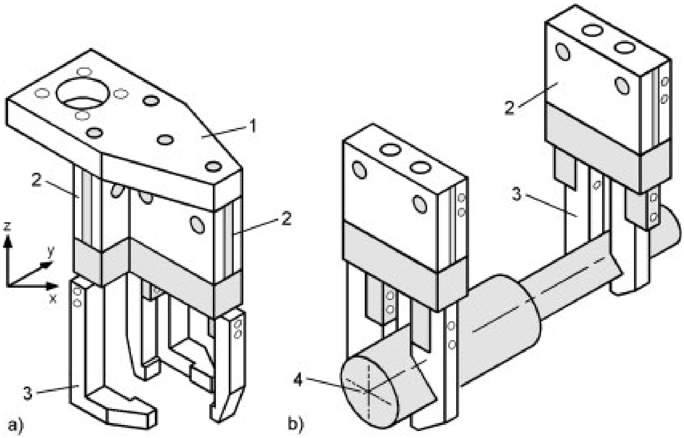
themselves are shaped to comply with the contour of the object, as shown in Figure 3.130 e. The active length of the gripping pins should be at least 5 mm.

3.2.10
Four-finger Grippers and Four-point Prehension

For the prehension of long objects, a four-point grasp can have some distinct advantages. This is usually achieved by means of two two-point grippers as shown in Figure 3.131.

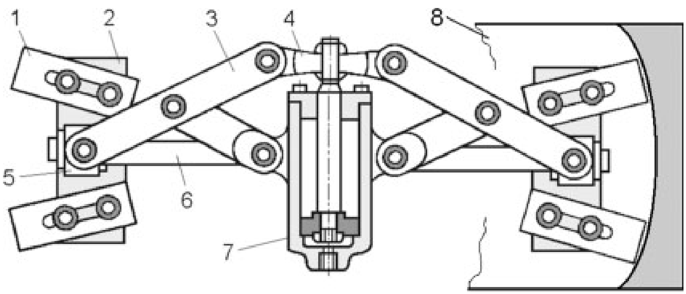
The laterally protruding jaws in the configuration shown in Figure 3.131 a provides centring in the x and y-axes (axial centring) when gripping rectangular parts. The four-point grip depicted in Figure 3.131 b is necessary in the case of long objects, particularly objects whose diameter varies along their length. A single two jaw gripper would normally be inadequate for this task because of the large moments of rotation should the mass centre of gravity not coincide exactly with the gripper centrum.

Hydraulically driven grippers are preferable for large and heavy objects. The gripper shown in Figure 3.132 can prehend large cylindrical parts internally. The driving piston rod of the hydraulic cylinder spreads the gripper jaws towards the curved internal surface of the hollow object. The lever mechanism is released on depositing the load so that the gripper jaws may move more freely.



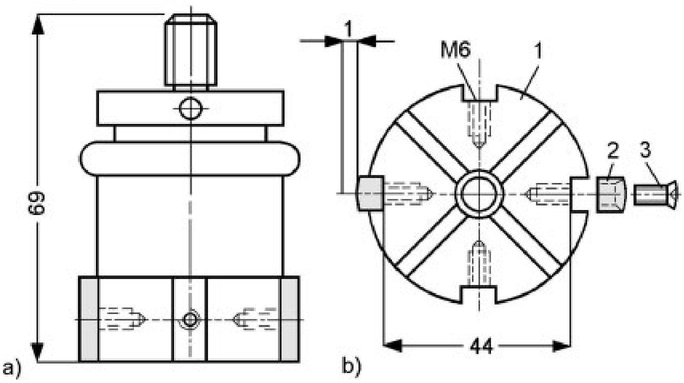
1 flange plate
2 parallel gripper
3 gripper jaw
4 workpiece

Fig. 3.131: Four-finger gripper combinations
a) gripper for rectangular parts, b) gripper for long cylindrical parts



1 gripper jaw
2 fastening plate
3 lever
4 connecting bracket
5 sliding block
6 guiding rod
7 hydraulic cylinder
8 prehended object

Fig. 3.132: Patented internal gripper with hydraulic actuator



1 housing
2 gripper jaw
3 fastening screw

Dimensions in mm

Fig. 3.133: Four-point gripper (*Sommer-Automatic*)
a) external view, b) view from below

The four-point gripper depicted in Figure 3.133 is also used for internal prehension. Actuation is realized through a nonsynchronized rubber membrane which spreads the four segments when a pneumatic pressure between 4 and 6 bar is applied. Prehension force can be maintained in case of energy failure by a pressure safety valve. However, the jaw travel is rather small and the gripping moment (4 Nm) is quite large.

There is rarely a single solution to a given prehension problem. Each individual case has its own peculiarities and demands often specific considerations. There are many variations in impactive gripper design and the interested reader should consult Chapter 14 where a large selection of case studies are explained.

4
Ingressive Grippers

Many objects are not solid in the conventional sense, in that they are made from fibrous materials. Examples include: textiles, carbon and glass fibre. Automated prehension, and moreover, separation from a stack of the same is not so simple because of their physical properties. The term *ingressive* is used to refer to those gripping methods which permeate a materials surface to some given depth. This includes intrusive means, such as pins, which can penetrate through the material and non-intrusive mechanisms which are normally incapable of penetration and merely "pinch" the material. The *ingressive* techniques distinguish themselves from *impactive* methods in that impactive prehension is achieved and maintained by force exerted against two or more surfaces on the same (usually rigid) object. The action of ingression normally applies to a single surface and allows the object to be held without the need to maintain an applied force.

Most pinch mechanisms actually permeate the material surface, though this permeation is usually restricted to a pre-determined depth, and preferably without damage to the material. For example a panel of textile fabric may be prehended by the penetration of small pins or by pinching with much coarser pins or teeth. In the latter case, the teeth tend to impress into the surface a small depth without full penetration. In both cases the gripping methods are ingressive.

Ingressive techniques are used almost exclusively with soft materials and in particular fabric, foam and fibrous components. Their history actually predates robotics in that their first use was in conjunction with crude mechanisation systems for textile handling and in many cases as a simple aid to the garment assembly operator. Consequently much literature and many patents exist in this field [4-1]. Some, more recent, literature surveys have concentrated on ingressive techniques which are directly applicable to robotics [4-2].

4.1
Flexible Materials

In the majority of cases, ingressive grippers are intended for the acquisition of the uppermost panel from a stack of the same. Ostensibly, ply separation is achieved by means of intrusion of the top panel to a controlled depth (see Chapter 10). Precision mechanisms are required which must be adjusted to suit the material with which the gripper is being used. However, this overlooks an extremely important factor in terms of the physical properties

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

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of most fabrics. When the uppermost panel is lifted by a gripper, those below tend to cling to it and to one another. Furthermore, it is essential that the top layer be removed cleanly, without disturbing the profile of those below. Otherwise, the next acquisition operation is likely to fail, or in the least result in prehension of a badly folded or distorted panel.

Until and unless single layer cloth cutting becomes practical and economical, fabric will continue to be die or knife cut from multiple layers. Consequently the most important task in any form of automated textile fabric handling is the removal of a single ply from a stack of the same. Without the ability to perform this basic task quickly and efficiently no totally automated system can function successfully as all subsequent operations depend on the accomplishment of this initial task. After a single ply has been removed from such a stack it must be positioned and orientated ready for the next operation. The subject of fabric ply separation will be dealt with in more depth in Chapter 10.

To summarise the problems involved with flexible materials and the demands placed on potential handling systems the following must be considered.

Fibrous materials have some or all of the following properties:
- extremely limp or stiff and with limited bend
- flocculent (hairy) surfaces which hinders separation
- air porosity making vacuum suction difficult
- stretchability resulting in undefined positional parameters

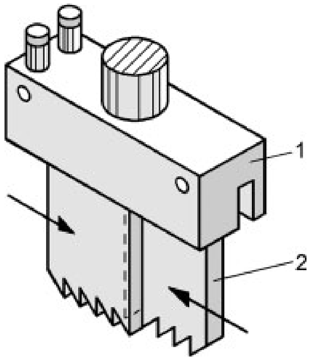
The demands placed on grippers for use with such materials are great:
- necessary prehension and retention force without damage
- flexibility to handle large ranges of object sizes and shapes
- high prehension reliability ($>$ 99%)
- short prehension cycles

Despite these problems many types of gripper exist which have been designed specifically for the handling of such materials. Others consist of changes to existing designs originally intended for other purposes.

4.1.1
Pinch Mechanisms

Taking the basic concept of the impactive gripper and replacing the gripper finger with a sharp spike would produce a crude form of ingressive device. However, it is possible to design more elegant ingressive mechanisms without going to this extreme. Use has been made of brushes, sandpaper etc., to help separate fabric from a stack. However, for reasons of potential damage, particulate contamination etc., such methods have been found largely unsatisfactory. Far more successful in this respect have been the mechanical pinch mechanisms, many of which were developed by Walton in the US [4-2]. One example consists of two serrated blades which are made to move both past and toward one another simultaneously causing the fabric to be pinched between them as shown in Figure 4.1.

Another variation on this theme is the very successful, patented CluPicker manufactured and marketed by the US textile machinery company "Jet-Sew" [4-3]. Here, a rotating serrated wheel pulls the fabric surface against a knurled foot to achieve a pinch effect.

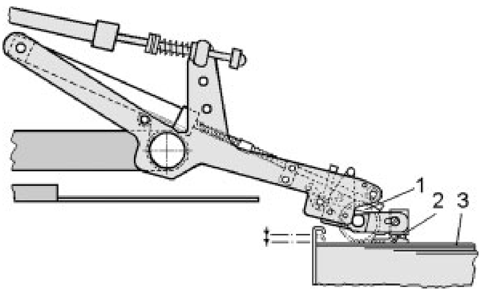


1 pneumatic drive
2 serrated plates

Fig. 4.1: Typical simple pinch gripper

Figure 4.2 shows the details of wheel and foot. Both the gap between the wheel and foot and the contact force are adjustable [4-4].

Having lifted the edge of the fabric, removal of the panel from the rest on a stack then depends heavily on the dexterity of the robot.



1 krurled wheel
2 foot
3 textile stack

Fig. 4.2: CluPicker mechanism

4.1.2
Intrusive Mechanisms

These are ingressive grippers, so designed that the prehension mechanism can be allowed to penetrate the surface, and in some cases through the full thickness of one or more layers of material. As such they usually consist of sharp needle points mounted on a rigid substrate or platform.

A wide range of multi-needle gripping devices have been developed over the years. The earliest models usually consisted of beds of needles deployed over a planar, cylindrical or belt type surface. Counter movement of two such surfaces over a layer of fabric allows the needles to penetrate in opposing directions thereby providing a means of very firm intrusive prehension [4-5].

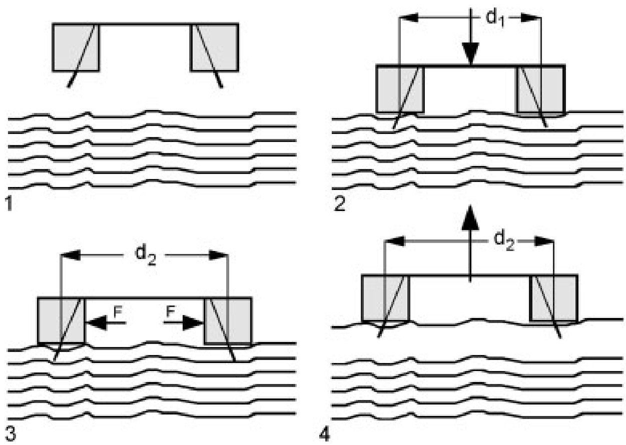
Hackles consist of cylinders or wheels containing many hundreds of small needle points, an example of which is shown in Figure 4.3. They have been used for many years in the recycling business for decimating paper, rags etc. [4-6]. By rotating and counter rotat-

Fig. 4.3: Typical ring hackles

ing many hackles at varying speeds, waste materials are torn into ever decreasing sized shreds in order to expedite later recycling processes [4-7]. Hackles have been used for fabric and leather manipulation [4-8] and for the removal of backing film from carbon fibre sheets during lay-up [4-9]. A similar mechanism, using two counter rotating hackles to grip the edge of a fabric panel was patented by Bijttbier during the mid 1970's [4-10].

By carefully limiting the depth of penetration, the needle principle may be used to produce grippers capable of offering a degree of ply separation. Typical intrusive grippers employ between 10 and 40 fine polished needles orientated in different directions. The needles have diameters ranging from 0.5 to 2 mm. The needle points are normally slightly rounded to prevent damage to the materials being handled. Depth of penetration is adjustable, typically between 0 and 5 mm.

There are a limited number of ways in which needles can be used for prehension purposes. Needles may be extended outwards from one another (Fig 4.6) or across one



1 approaching the stack
2 contact and penetration
3 stretching of material between needles
4 removal from stack
F material stretching force

Fig. 4.4: Application of needle gripper to ply separation

another (Fig 4.7). The basic principle is best explained with help from Figure 4.4 in which the maximum gripper stroke is $(d_2 - d_1)/2$.

The prehension force is dependant on the number of needles, their distance apart and the needle penetration angle.

With help of the diagram and curve given in Figure 4.5, the prehension force F_H for the acquisition of textile panels can be calculated from the following equations:

$$F_H = \sigma \cdot A_N \cdot n_N \qquad [N] \tag{4.1}$$

$$\sigma = \frac{E_{Z6\%} \cdot d}{2 \cdot s \cdot \sin \alpha_N} \tag{4.2}$$

$$A_N = \frac{d^2 \cdot \tan\left(\frac{\gamma}{2}\right)}{\sin \alpha_N} \tag{4.3}$$

σ mechanical stress (pressure) [N/m^2]
A_N cross sectional area of a needle [m^2]
$E_{Z6\%}$ effective Young's modulus of the textile material at 6% mechanical strain [N/m^2]
d ply thickness [m]
s distance between needles [m]
n_N number of needles
α_N penetration angle of needles
γ angle of needle point (sharpness)

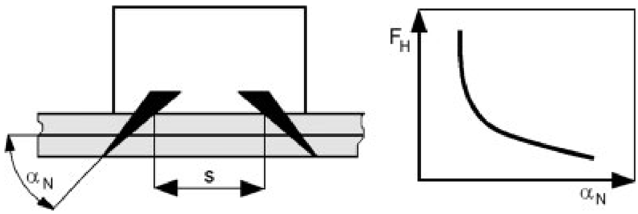


Fig. 4.5: Main parameters for an intrusive needle gripper

Figure 4.6 shows the design of an intrusive gripping head, originally designed by Littlewood, in which several needles are made to extend radially by the movement of a pneumatic actuator [4-11]. On cessation of the pneumatic signal the needles are retracted by means of a return spring and the object falls free from the gripper. In most cases the needle penetration depth is adjustable. By using a precision drive mechanism a minimum needle stroke of less than one thousandth of an inch is claimed [4-12].

A more cost effective version, originally developed for the transferring of absorbent foam pads used to line the bottom of meat crates in the food industry, is the Rhoden "Piklift" device [4-13]. Due to its robustness, this and similar grippers have also found applications in composite material handling and in particular carbon fibre tow used for the man-

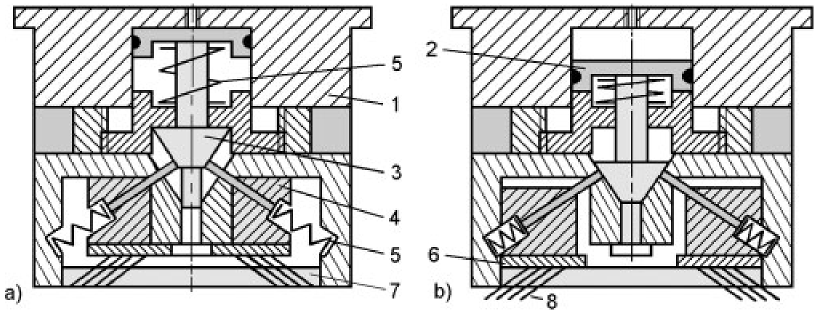
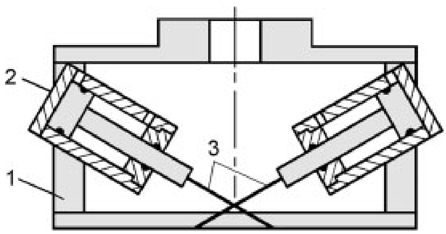


Fig. 4.6: Design of an intrusive needle gripper
a) needles retracted, b) needles driven outwards
1 gripper housing, 2 piston, 3 wedge, 4 feedthrough bush, 5 return springs,
6 needle plate, 7 gripper surface, 8 needles

ufacture of brake linings in the aircraft industry [4-14]. The needles protrude at an angle of 30° and depth of penetration is adjustable between 0 and 6 mm.

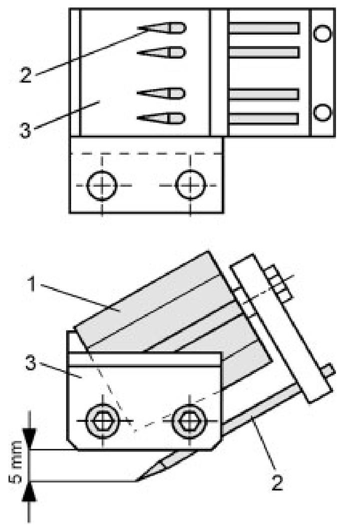
A variation on the extendible needles principle shown in Figure 4.7 is the Swiss made Polytex device [4-15]. This is an ingressive gripper which relies on intrusion for the separation of single panels of textile material from a stack of the same. The syringe-like hollow needles fully penetrate the surface of the uppermost panel before a blast of air is forced through them to assist in the separation of this panel from those remaining on the stack [4-11]. Hollow needles are also used in order to effect pneumatic ply separation in a system using a bed of needles [4-16]. In both cases the penetration depth is adjustable.



1 housing
2 pneumatic cylinder
3 needles

Fig. 4.7: Foam gripper

It is interesting to note that the effect of hollow needles can be used in reverse. By the application of vacuum suction to the hollow needles immediately after surface penetration, for evacuating the surplus air from polymer bags during handling and transportation of bagged goods [4-17]. This permits a considerable increase in packing density for such products.



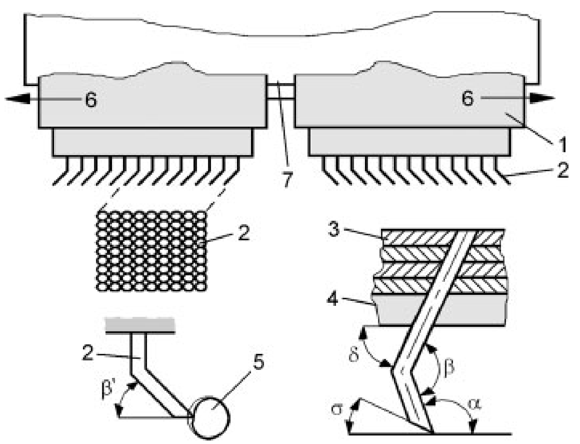
1 pneumatic cylinder
2 needles
3 gripper substrate

Fig. 4.8: Ingressive gripper (*ASS*)

4.1.3
Non-Intrusive Mechanisms

Figure 4.8 shows a needle gripper which consists of a number of small parts. Its intended application is in the prehension of plastic parts produced by pressure or blow moulding. The needle plate is driven by a pneumatic cylinder mounted on the gripper substrate.

An alternative form of the ingressive principle which is not normally intrusive utilises a bed of very fine needles, rather like the hackles previously discussed, or wire brushes [4-18] [4-19] distributed on a planar surface as shown in Figure 4.9.



1 gripper jaws (e.g. 16 mm stroke)
2 angled wire brush
3 6 cotton layers
4 rubber underlay
5 surface thread(s)
6 jaw movement
7 parallel gripper

α ingression angle (100–115°)
δ set angle (72°)
β bend angle (135–150°)
σ point angle
β' penetration angle ($<$ 60°)

Fig. 4.9: Fine needle gripper

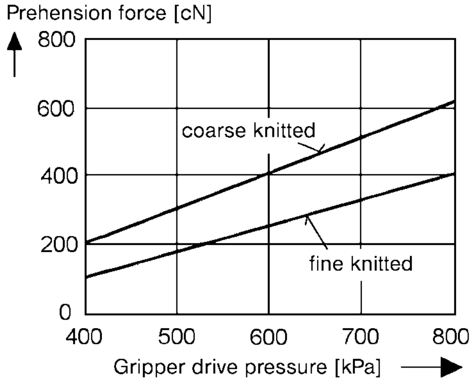


Fig. 4.10: Prehension force diagram for a wire brush gripper

The basic gripper is a standard impactive parallel device whose jaws carry the two wire brushes. The wires have diameters of typically 0.3 to 0.5 mm. The prehension force is difficult to calculate but an idea can de obtained from the graph shown in Figure 4.10.

To some extent the prehension force F_H can be calculated as follows:

$$F_H = F_{VK} \cdot (\sin \alpha_K \cdot \cos \alpha_K - \mu_G \cdot \sin^2 \alpha_K) \qquad [N] \tag{4.4}$$

$$F_{VK} = \frac{d \cdot b_K \cdot E_{z6\%}}{2 \cdot \varepsilon \, (F_N \cdot \chi)} \cdot n_K \qquad [N] \tag{4.5}$$

whereby:

b_K material movement under stress [m]
n_K number of fine points
ε mechanical strain [%]
$E_{z6\%}$ effective Young's modulus of textile material at 6% strain [N/m^2]
F_{VK} mechanical force produced by the gripper [N]
μ_G effective frictional coefficient of fabric
α_K ingression angle of fine points
χ angle of fabric warp to weft (in woven fabrics)

Many of the above mentioned properties, such as mechanical moduli, are rarely available and often impossible to accurately measure. This is particularly true where a large degree of anisotropy, such as with knitted materials, exists. Further details can be obtained from specialist texts on the subject [4-20].

The use of ingressive grippers with very fine mesh materials, such as nylon stockings, is very problematic. The yarn is so fine that even the best rounded and polished needles tend to result in unwanted ladders during handling. For such materials contigutive methods, as described in Chapter 6, are a possible alternative.

5
Astrictive Prehension

As the name implies, astrictive grippers have the property of providing a continuous holding force without the application of compressive stress. Vacuum suction is one of the oldest astrictive gripping methods, and is used extensively throughout industry. Other astrictive methods include magnetoadhesion [5-1] and electroadhesion [5-2]. Unlike many impactive methods, almost all forms of astrictive devices rely on some degree of continuous energy supply to maintain object retention.

5.1
Vacuum Suction

These are basically vacuum suction heads which hold the object through astrictive surface forces, rather than impactive forces, with selective contact points. The suction heads themselves are normally elastomeric suction cups or caps. Such endeffectors, also known as suction grippers, require only rough vacuum (rarely less than 100 mBar) and in general, typical vacuum conditions for pneumatic astrictive grippers is about 70% of atmosphere (a vacuum of 0.7 bar or an absolute pressure of 0.3 bar).

The following table can be used for conversion of vacuum percentage values (DIN 28 400). For example: a vacuum of 60% corresponds to a pressure of 608 mbar.

Conversion table

Absolute residual pressure in mbar	900	800	700	600	500	400	300	200	100
Relative vacuum in %	10	20	30	40	50	60	70	80	90
Pressure in bar	−0.101	−0.203	−0.304	−0.405	−0.507	−0.608	−0.709	−0.811	−9.12
Pressure in N/cm²	−1.01	−2.03	−3.04	−4.05	−5.07	−6.08	−7.09	−8.11	−9.12
Pressure in kPa	−10.1	−20.3	−30.4	−40.7	−50.7	−60.8	−70.9	−81.1	−91.2

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

ISBN: 978-3-527-40619-7

Vacuum grippers can be used for large and heavy parts, and also for very small components in the semiconductor industry and microassemblies [5-3]. Their principle is relatively simple. In contrast to many impactive techniques, centring of the object is not normally carried out as part of the prehension process. Systems intended for the handling of very small components (with correspondingly small gripper nozzles) should use clean, filtered air in order to avoid blockages. Old pneumatic supplies with integrated oilers (as used in the 1950s) should not be employed with modern vacuum SMD automation!

5.1.1 Vacuum Production

Theoretically, the required vacuum can be produced by any of the following methods:
- Vacuum pumps and blowers.
- Venturi vacuum suction generators (ejectors).
- Suction bellows.
- Pneumatic cylinders.

These principles are shown schematically in Figure 5.1.

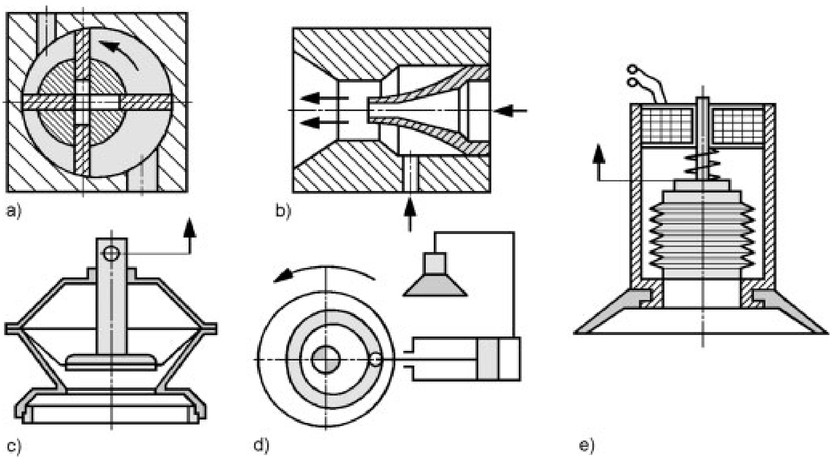


Fig. 5.1: Possibilities for vacuum production
a) rotary slide valve or other pump, b) venturi ejector, c) suction through bellows, d) piston suction system, e) suction through electromagnetic actuation

The use of **vacuum pumps** has the following advantages:
- Higher vacuum is possible.
- Low operational costs, little noise development.

The disadvantages are related to the high initial costs and the expenses for further accessories, e.g. air reservoirs. Some companies are equipped not only with central compressed air line but also with their own vacuum line, e.g. in the light bulb industry. In this case it is not necessary to have separate vacuum production. The size and weight of a pump also makes mounting directly at the gripping head difficult. Long pneumatic lines make for slow response times.

Vacuum blowers produce relatively low vacuum as can be seen from the comparison in Figure 5.2. However, their exhaustion rate is high. Consequently, they are advantageous in applications where porous workpieces are to be handled because it is possible to compensate for losses owing to air permeability.

The **Venturi** principle, on which the ejector is based, dates from *Giovanni Battista Venturi* (1746–1822), an Italian physicist who worked on problems related to the hydrodynamics and hydraulics. The same principle is also used for flow velocity measurements.

Venturi vacuum generators **(ejectors)** possess the following advantages:
- Easy mounting; no moving parts and hence low initial costs.
- No additional equipment necessary; fast response.
- Direct integration into the gripper possible and, to a large extent, trouble-free operation.

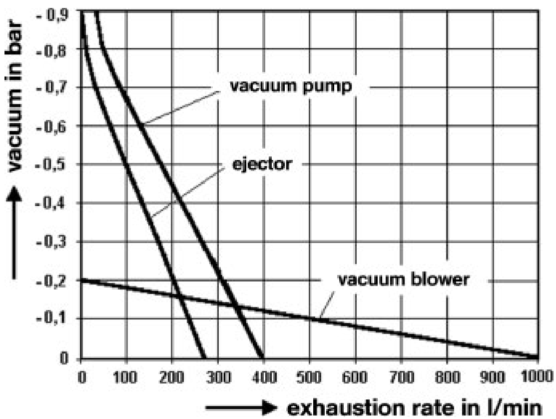
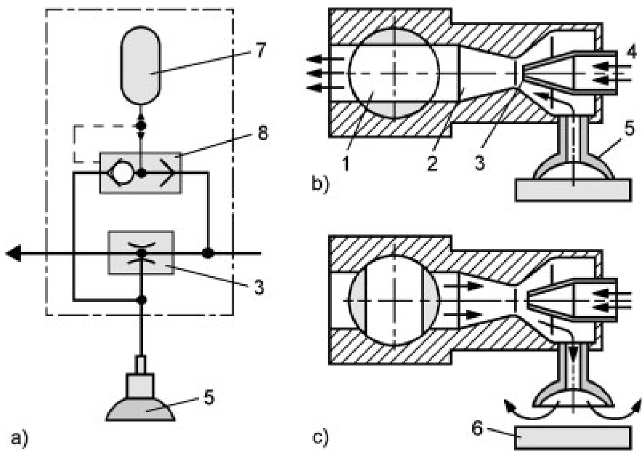


Fig. 5.2: Comparison of the performance specifications of typical vacuum generators

The disadvantages are related to the high operational costs (compressed air consumption) and the required noise damping. The suction nozzle must be designed to take into account the peak load because there is no vacuum reservoir. The vacuum is generated inside the ejector as the compressed air passes through the narrow cross sectional area of the driving nozzle. The narrowing of the channel leads to increased flow velocity resulting in an expansion of the air flowing through the receiver nozzle. If the exit air channel is blocked (Fig. 5.3), this leads to a blow-off effect. If the compressed air is turned off the suction cup is aerated through the air exit nozzle.

Ejectors can have multiple stages and can be arranged in parallel rows. Multi-stage ejectors (multi-chamber ejectors) contain several suction nozzles connected in series (Fig. 5.4 b). They are characterized by high suction power, high volume flow and fast response times. This results in shorter evacuation times and hence shorter handling cycle times. In addition safer holding, even for dynamic motion sequences, is ensured. In



1 stop valve
2 receiver nozzle
3 driving nozzle
4 compressed air supply
5 suction cup
6 workpiece
7 reservoir
8 air escape valve

Fig. 5.3: Ejector with blow-off function
a) integrated storage volume
b) combination with a stop valve
c) switching to blow-off

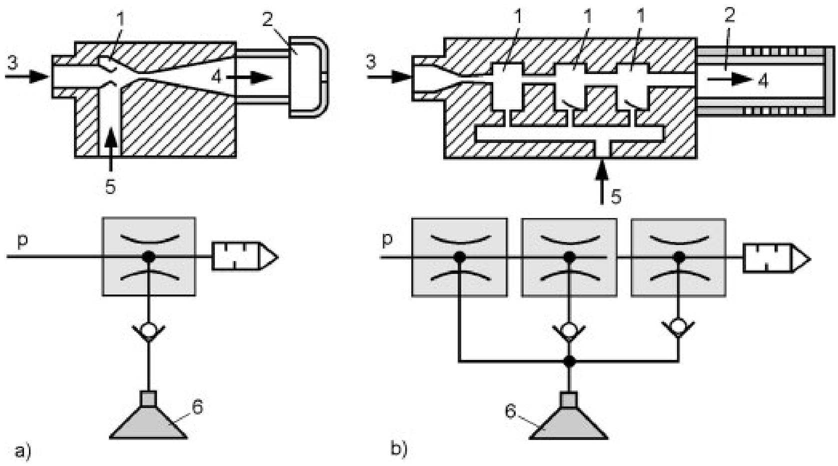


Fig. 5.4: Construction of an ejector
a) single-stage ejector, b) multi-stage ejector
1 cross sectional narrowing of the driving nozzle, 2 absorbing duct, 3 compressed air inlet, 4 air exit, 5 vacuum, 6 suction cup, p pressure

general, the evacuation time increases disproportional to the increase in required vacuum. Hence, for efficient operation the generated vacuum should correspond to the minimum required level.

In cases where a short burst of higher suction power is required a pressure accumulator can be included as shown in Figure 5.5.

Porous and permeable materials, such as teabags or filter blotting paper, require substantial suction power which must be provided continuously. In addition to the more expensive vacuum pumps, a low cost and low maintenance alternative is a plurality of suction nozzles connected in parallel as shown in Figure 5.6.

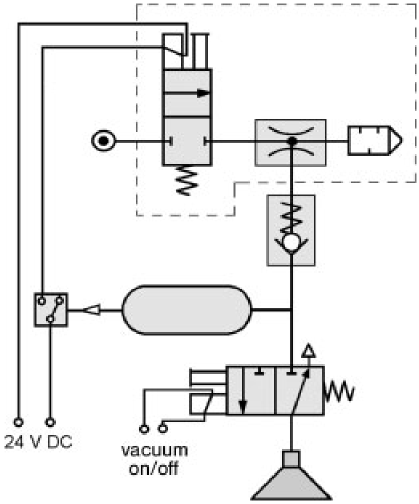


Fig. 5.5: Pneumatic diagram of a vacuum system in which the suction power is momentarily increased with the help of a pressure accumulator

Ejectors which store the compressed air and then release it as a pressure impulse when depositing the object are called "suction heads". They ensure fast and safe separation of the acquired objects. This auxiliary function, as well as the gripper itself, is relatively maintenance free. The drop impulse can be increased by the connection of an additional volume of air.

Larger astrictive grippers, consisting of several separate suction caps, are often designed for the prehension of large sheet metal parts. The complete pneumatic circuit required for this is shown in Figure 5.7. The suction cups are attached to a plenum chamber manifold.

Vacuum may be produced by force acting on a flexible membrane which attempts to increase its hollow volume. Alternatively, the mechanical stretching of bellows by an electromagnet can be used to generate suction. The advantages of this technique lie in its simplicity, inexpensive components and low running costs. The advantage of no sustaining vacuum becomes a disadvantage for objects with uneven surfaces where leaks in the vacuum pressure may occur. As a rule the roughness depth should not exceed 5 μm.

Piston suction systems are occasionally used, e.g. in mounting robots. They produce alternating vacuum and release air which is synchronized to the machine over a line. The stroke and the temporal sequence are stored as information in the form of a radial cam.

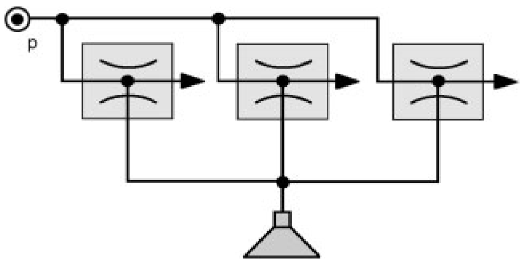
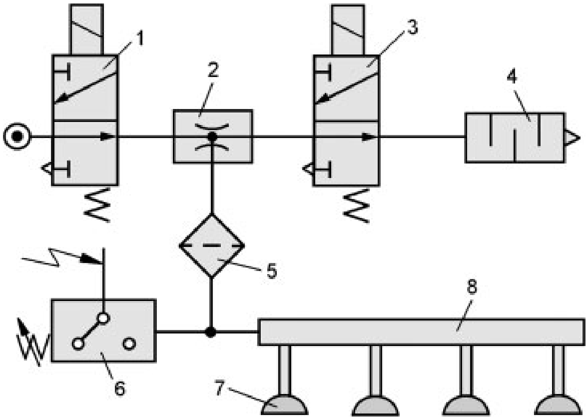


Fig. 5.6: Parallel combination of suction nozzles
p compressed air supply

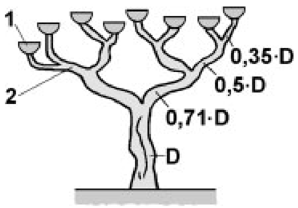


1 compressed air direction control valve
2 ejector
3 exit air direction control valve (blow-off control)
4 absorbing duct
5 suction filter
6 push switch for vacuum
7 suction cups
8 distributor

Fig. 5.7: An example of a vacuum circuit based on an ejector

A machine equipped with a piston to develop suction does not depend on a compressed air generator (vacuum produced by an ejector or pump). Some limited compensation for leakage may be provided depending on the stroke of the piston.

The lifting of large area workpieces normally requires several suction heads with simultaneous vacuum distribution. There is a trade-off in terms of line diameters. Too small a diameter and air flow resistance is increased. Too large and evacuation time in increased. A good analogy is that of a tree (Fig. 5.8) which must supply sap to every leaf.



1 suction cup
2 air line

D tube diameter

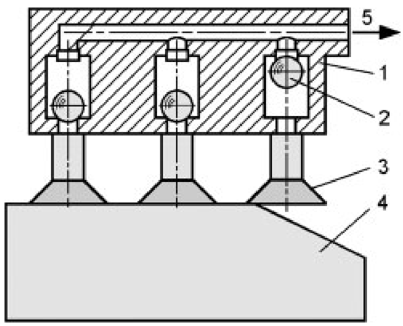
Fig. 5.8: Correct choice of the tube diameter is important for the distribution of vacuum

A rough rule of thumb is that each level of branching requires a diameter which is 1.42 times narrower than its parent line.

Non-return valves can be used to ensure additional vacuum retention safety should one or more suction caps in a group be inactive, e.g. if the suction gripper is not accurately positioned or the surface of the object is uneven at this point. As shown in Figure 5.9 a floating ball is sucked against a nozzle thus sealing the vacuum where contact with the object fails. A slight degree of porosity in the ball ensures some weak residual air flow which, however, has a negligible effect on the underpressure of the system. This helps avoid the need for over dimensioned pumps in order to compensate for the leakage.

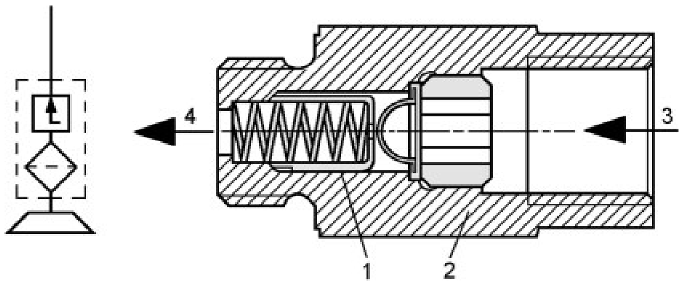
Such non-return flow control valves can also be purchased separately as standard pneumatic components, as can be seen in Figure 5.10.

Figure 5.11 shows the pneumatic diagram for a configuration employing a plurality of vacuum suction caps and non-return flow valves driven from a single ejector. The distribu-



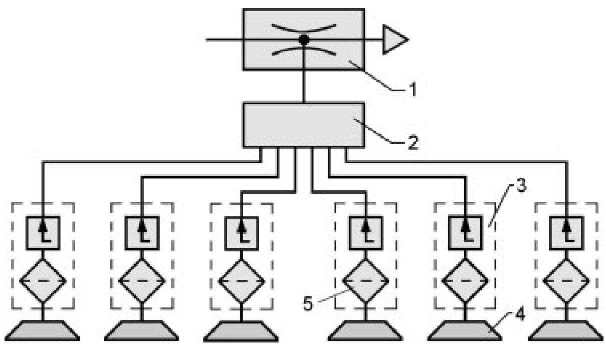
1 housing
2 light porous ball
3 suction caps
4 workpiece
5 vacuum

Fig. 5.9: Automatic shut-off of inactive suction cap



1 float
2 carrier
3 suction side
4 tube connection side

Fig. 5.10: Cross section of a vacuum suction valve (*Festo*)



1 vacuum generator
2 plenum chamber distributor
3 vacuum suction valve
4 suction cup
5 filter

Fig. 5.11: Function diagram for the connection of suction cups over vacuum suction valves

tor is also a plenum chamber which acts as a reservoir thus helping to maintain homogeneity of vacuum pressure for all suction caps.

Finally, Figure 5.12 illustrates a complete vacuum system. An ejector (single-stage, multi-stage) or an electric vacuum air supplier (pump, blower etc.) can be used alternatively for vacuum generation. An accumulator tank can help maintain a constant vacuum despite pressure fluctuations. Moreover, any additional storage volume considerably reduces evacuation time because the system can react to momentary peaks in flow rate.

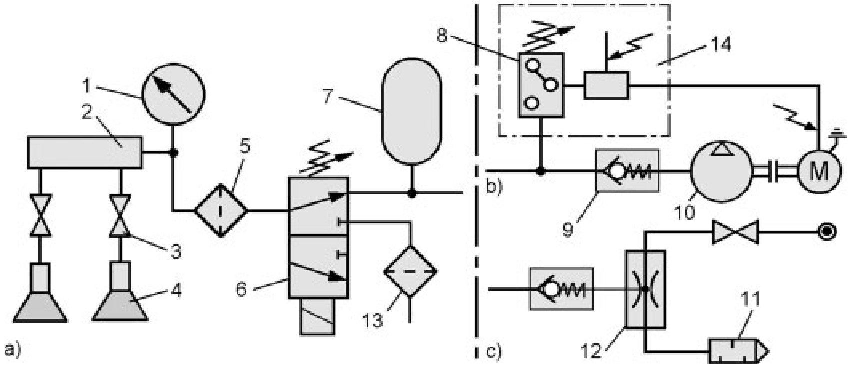


Fig. 5.12: Vacuum circuit with two supply options
a) vacuum from supply, b) electric vacuum generation, c) pneumatic vacuum generation
1 vacuum gauge, 2 distributor, 3 stop valve, 4 suction cup, 5 air filter, 6 vacuum control valve, 7 vacuum accumulator tank, 8 press switch, 9 return valve, 10 vacuum pump, 11 absorbing duct, 12 ejector, 13 air filter, 14 pressure dependant motor control

5.1.2 Vacuum Suckers

Ease of implementation, gripping strength and low cost makes this the commonest astrictive retention method used in robotics and automation. In its simplest manifestation, a flexible suction cup is forced against a surface. Air is expelled as the flexible polymer cup is compressed. On cessation of the applied force the cup tries, by means of its own mechanical elasticity, to regain its original shape. Being now sealed against the object surface it is unable to do so, thus forming a slight negative pressure within the cup. This negative pressure provides the holding force necessary for object prehension and retention.

- The upper limit for the prehension force is determined by the surrounding air pressure and the maximum surface area which can be accessed for gripping.
- Manipulation of objects inside the gripper is impossible.
- The highest operational temperature for suction cups made from NBR (nitrile rubber) is around 130 °C, for silicone up to 280 °C and even as high as 300 °C for FKM (fluorine rubber). Suction disks made from high-temperature silicone with a special felt overlay (*FIPA-Vakuumtechnik*) have also been specially developed for applications up to 550 °C. These materials are vulcanized on a steel-plate and the felt ensures an almost indentation free grip, which is particularly advantageous in the handling of delicate parts.

Lifting pressure on an object is given by the ratio of retention force to gripper-object contact surface area. Though gripping force F is often used as a design parameter, pressure σ is more appropriate for the purposes of general comparison between astrictive gripper types as it is independent of individual device surface areas.

Taking into consideration the effects of gravity g, and the acceleration of the robot a, on an object of mass m, the contact pressure σ is obtained from expression (5.1).

$$\sigma = \frac{F - m \cdot (g + a)}{A} \tag{5.1}$$

A prehension surface area
g acceleration due to gravity
a acceleration of the handling equipment

For all astrictive grippers, power is consumed during both prehension and retention. A ratio of steady state power consumption and retention pressure gives the volumetric flow rate Q, which may also be used as a figure of relative merit as expressed in (5.2).

$$Q = \frac{dV}{dt} = \frac{P}{\sigma} \tag{5.2}$$

The energy efficiency of the gripper decreases with increasing Q. All astrictive mechanisms experience finite response times for prehension and release. They have an initial prehension flow rate Q_o, whose delay (or rise) time is usually exponential, and a steady state value during object retention Q_s. In most cases the corresponding time constant τ will be different for prehension and release.

For a typical vacuum suction cup, the initial static prehension force F on an object of surface area A is given by (5.3).

$$F = (\sigma_0 - \sigma_u)\, A \tag{5.3}$$

is approximately fulfilled where:

σ_0 atmospheric pressure [bar], depends on the geographical height
σ_u applied vacuum pressure [bar] within the sealed suction volume
A effective interface area between suction cap and object surface [m^2]

In practice, the applied vacuum ranges from 10% (− 0.101 bar) to 90% (− 0.912 bar). However, negative pressures exceeding 60% are expensive to achieve and where possible their expectation should be avoided in the design stages.

As soon as prehension is achieved and motion commences a number of additional forces come into play. All suction heads, and especially soft lipped (bell-shaped suction cups), experience strong deformation under pressure. This can, together with leakages, surface contaminants etc., lead to a reduction in the effective suction force.

$$F = (\sigma_0 - \sigma_u) \cdot A \cdot n \cdot \eta \cdot z \cdot \frac{1}{S} + mg \tag{5.4}$$

n deformation coefficient ($n = 0.9$ to 0.6)
S safety factor. Typically: $S = 2$ to 3
z number of suction cups
η system efficiency (leakage losses etc.)

The diameter d of a circular suction cap can be estimated (approximately) from the following equation, assuming a static situation or slow motion in the vertical direction:

$$d = 11.3 \sqrt{\frac{m \cdot S}{\sigma_u \cdot z}} \qquad [\text{mm}] \qquad (5.5)$$

m workpiece mass [kg]

The retention force is a function of the area of the surface interface. All additional forces acting on the object must also be taken into account. Two standard cases (Fig. 5.13) are of interest here:

Case 1: The gripper-object interface is horizontally aligned.
Case 2: The gripper-object interface is vertically aligned.

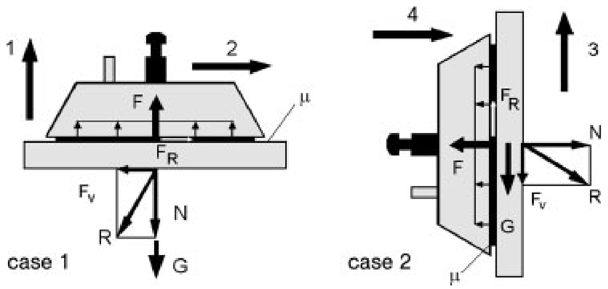


Fig. 5.13: Retention using vacuum
F retention force, suction force, F_v tangential force, F_R friction force, G force on the object due to gravity, N normal force, R resultant force, μ friction coefficient at interface, 1 to 4 application dependant directions of motion

The friction coefficient μ plays no role in equation (5.5) where only cohesive forces are considered. Only where shear forces exist, particularly in the second case with a rotation of 90°, does friction become important. For glass, stone and plastics (clean, dry) it can be assumed that $\mu = 0.5$. This value can drops to around $\mu = 0.1$ for wet and oily surfaces. The table in Figure 5.14 summarizes several typical dynamic situations.

In extreme cases where oiled steel sheets are concerned there can be additional problems. The steel sheets tend to "swim" away from the suction cup as it approaches. The lips of the suction cups fail to penetrate the oil film and the simple *Coulomb* law of friction no longer applies. However, for most applications this is rarely the case and the necessary gripping forces can simply be estimated according to manufacturer's data or calculated from the given expressions.

The flow rate Q can be also expressed as a function of the opening width A_a, the pressure difference s and the air density ϱ [5-4] as in (5.6):

$$Q = A_a \cdot \sqrt{\frac{\sigma}{\varrho}} \qquad (5.6)$$

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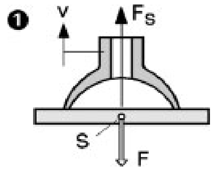
<tr><td>
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$F_S \geq n_1 \cdot F$

F sum of all forces leading to detachment and displacement
F_S vacuum generated force
n_1 security coefficient opposing detachment

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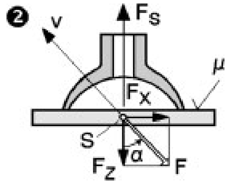
<tr><td>
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$F_S \geq F\,(n_1 \cdot \cos\alpha + (n_2/\mu) \cdot \sin\alpha)$ or
$F_S \geq n_1 \cdot F_Z + (n_2/\mu) \cdot F_X$

n_2 security coefficient opposing displacement
μ friction coefficient (suction cup/workpiece)

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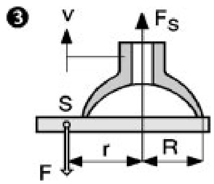
<tr><td>
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$F_S \geq n_1 \cdot k_1 \cdot F$
$k_1 = 1 + (r/R)$

k_1 eccentricity coefficient at force onset
r distance between prehension and object centre
R external radius of suction cup

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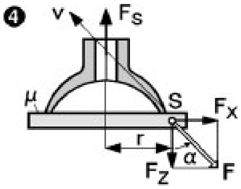
<tr><td>
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$F_S \geq n_1 \cdot k_1 \cdot F_Z + (n_2/\mu) \cdot F_X$ or
$F_S \geq F(n_1 \cdot k_1 \cdot \cos\alpha + (n_2/\mu) \cdot \sin\alpha)$

α angle of force acting relative to the normal
S prehended object mass centre

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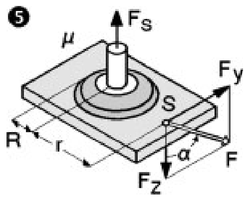
<tr><td>
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$F_S \geq n_1 \cdot k_1 \cdot F_Z + (n_2/\mu) \cdot k_2 \cdot F_Y$ or
$F_S \geq F(n_1 \cdot k_1 \cdot \cos\alpha + (n_2/\mu) \cdot k_2 \cdot \sin\alpha)$

$$k_2 = 1 + \frac{r}{R} + \frac{F_Z}{F_Y} \cdot \mu$$

k_2 eccentricity coefficient at force onset

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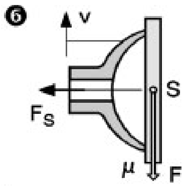
<tr><td>
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$F_S \geq n_2 \cdot F/\mu$

special case of ❷ at $\mu = 90°$
In most cases, the horizontal axis suction cup retention force is less than 50% of the equivalent force for a vertical retention axis.

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Fig. 5.14: Typical force settings for a suction gripper
μ linear acceleration, S centre of gravity, v velocity

The evacuation time t depends on the change of the flow rate which has an initial value of Q_0. It is determined from:

$$\frac{dQ}{dt} = \frac{d^2V}{dt^2} = Q_0 \cdot e^{-t/\tau} \tag{5.7}$$

Integrating and rearranging the last equation gives

$$Q = \tau \cdot Q_0 \cdot e^{-t/\tau} + k \tag{5.8}$$

where τ is a time constant dictated by the elasticity of the suction cup material, aperture size, air line dimensions etc. The constant of integration k represents the steady state flow Q_S, due to quiescent losses, after object acquisition.

For example, a typical 100 mm diameter conical suction cup has a volume of 1.3×10^{-4} m³. Assuming a 10 mm diameter orifice, a differential pressure of 50 kN/m² and an air density at 20 °C of 1.2 kg/m³ [5-5] then expression (5.6) yields a flow rate of 0.016 m³/s. Even with a relatively long time constant the time needed to empty this volume of air will be in the order of tens of milliseconds. If the steady state flow rate during retention Q_S is only 10% of this value, expression (5.2) gives a power dissipation of 80 Watts for this device.

Example: A conical vacuum suction cup has a diameter of 5 cm and air is evacuated to an underpressure of 0.1 bar. A simplified calculation yields:

$$F = \left(100\frac{\text{kN}}{\text{m}^2} - \frac{10\,\text{kN}}{\text{m}^2}\right) \cdot \frac{0.05^2 \cdot \text{m}^2 \cdot \pi}{4} \approx 180\,\text{N} \tag{5.9}$$

The surface pressure is

$$\sigma = \frac{F}{A} = \frac{180}{0.00196} = 92\,\text{kN} \cdot \text{m}^{-2}$$

Assuming a symmetrical conical shaped vacuum cup with $H = 2 \cdot r$, the air volume to be evacuated is given by (5.10)

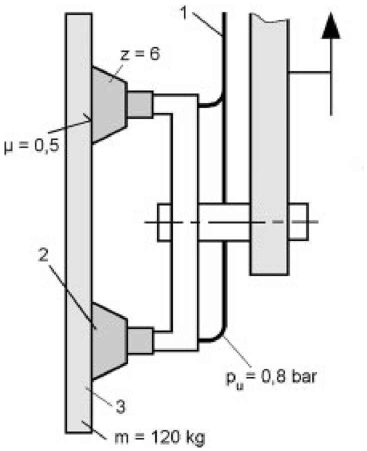
$$V_c = \frac{\pi \cdot r^2 \cdot h}{3} = \frac{\pi \cdot 2.5^2 \cdot 2 \cdot 2.5}{3} = 32.7 \cdot 10^{-6}\,\text{m}^3 \tag{5.10}$$

For a prehension time of 1s the required flow rate calculated from (5.10) is Q ca. $33 \cdot 10^{-6}$ m³/s. This gives a power consumption of

$$P = Q \cdot \sigma = 33 \cdot 10^{-6}\frac{\text{m}^3}{s} \cdot \frac{92\,\text{kN}}{\text{m}^2} = 3036\frac{\text{kNm}}{s} \cdot 10^{-6} = 3\,\text{Watt}$$

These results are also theoretical values. They do not take into account the leakage losses and the evacuation of the feed lines or tubes. The gripping time is very important for rapid processing which is why a Venturi nozzle or a vacuum sequence valve should be accommodated in the direct vicinity of the suction cup. Prehension can be accelerated by making a trade-off with the gripper efficiency if the handling cycle time gain justifies it [5-6].

Example: Estimation of the required suction cup diameter for the case depicted in Figure 5.15. A-priori it is assumed that the size of the steel sheet to be lifted makes it necessary to use six suction caps. The metal sheet has to be lifted in a relatively slow manner in the perpendicular direction. A necessity of doubled security factor *S* is assumed.



1 vacuum line
2 vacuum suction cap
3 workpiece (sheet product)

Fig. 5.15: Lifting of load by vacuum suction

For the suction cap diameter *d* this gives:

$$d = 11.3 \cdot \sqrt{\frac{m \cdot S}{\varrho_u \cdot z \cdot \mu}} \tag{5.11}$$

Substituting the given values:

$$d = 11.3 \cdot \sqrt{\frac{120\,\text{kg} \cdot 2}{0.8\,\text{bar} \cdot 6 \cdot 0.5}} = 113\,\text{mm}$$

The next larger available diameter which can be selected for the six suction caps is 120 mm. The upper surface of the sheet should be clean and dry. The friction coefficient can be considerably lowered for wet and oily surfaces as shown in the following table.

Suction cap type	**Surface conditions**	**Friction coefficient for roughness depth**	
		$Ra = 0.05\ \mu m$	$Ra = 1.5\ \mu m$
Stiff	Oil-free	0.85	–
Easily deformable	Oil-free	0.45	0.65
Stiff and light	Oiled with bore emulsion	0.15	0.35
Deformable stiff	Oiled with cooling fluid	0.05	0.25
Light deformable	Oiled with cooling fluid	0.025	0.15

In some cases the geographical height of the site can also play a role because the actual air pressure depends on the height of the air column above the corresponding elementary surface. The normal pressure always refers to sea level and amounts to 1013 mbar (DIN 1343). Hence, the load capacity decreases with increasing geographical height, for which the following relationship holds:

Height above SL	**Relative load capacity**
0 to 250 m	100%
250 to 500 m	96%
500 to 750 m	92%
750 to 1000 m	88%
1000 to 1250 m	84%
1250 to 1500 m	80%

A selection of the numerous designs of suction cups, caps and discs are presented in Figure 5.16. In addition, there are suction cups which are shaped to fit a specific object (or a recess in the object) and those which can adapt themselves to the shape of the workpiece. The segmentation of the astrictive surface can be also advantageous for reasons of prehension reliability.

Large surface objects can be handled with one large oval suction head or by employing a plurality of smaller suction discs or caps. The suction cups with integrated bellows have between $1\,^1/_2$ and $3\,^1/_2$ conical sections. They are used for the handling of delicate objects and/or in circumstances where slight differences in workpiece heights must be compensated for. The elastic vertical stroke s provided by bellows is an interesting attribute which can be exploited in order to acquire the workpiece from an uneven surface or lift it directly from a seat without necessarily making an initial air tight contact. This is illustrated in Figure 5.17.

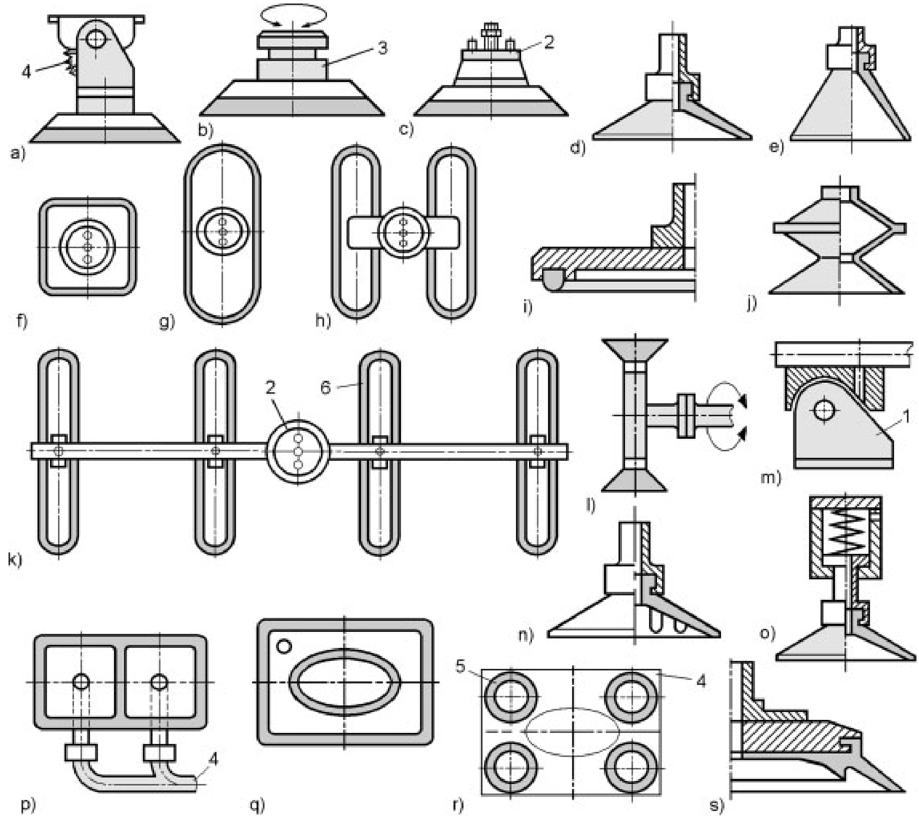
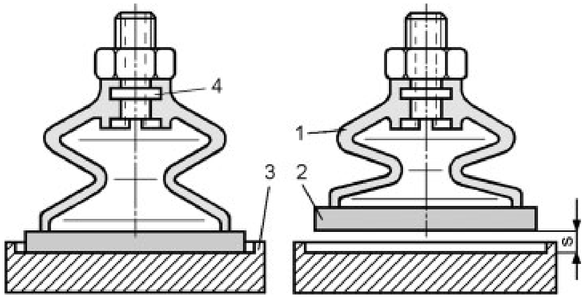


Fig. 5.16: Typical suction head designs: above and cross-sectional views
a) suction disc with swivel axis, b) suction disc with 360° axial rotation unit, c) simple suction base, d) flat suction cup, e) deep suction cup, f) rectangular suction head (view from above), g) oval suction head, h) double oval suction head, i) suction head with cell rubber washer, j) bellows suction cup, k) multiple suction heads for large parts, l) double suction gripper, m) shaped workpiece suction head, n) suction cup with support ribs, o) suction head with integrated vacuum generation, p) segmented suction plate, q) ring surface suction head, r) combination of separate suction heads, s) double lip suction cap
1 workpiece, 2 mounting collar, 3 swivel joint, 4 vacuum tube, 5 suction cup



1 suction bellows
2 prehended object
3 workpiece seat
4 inner metal connection

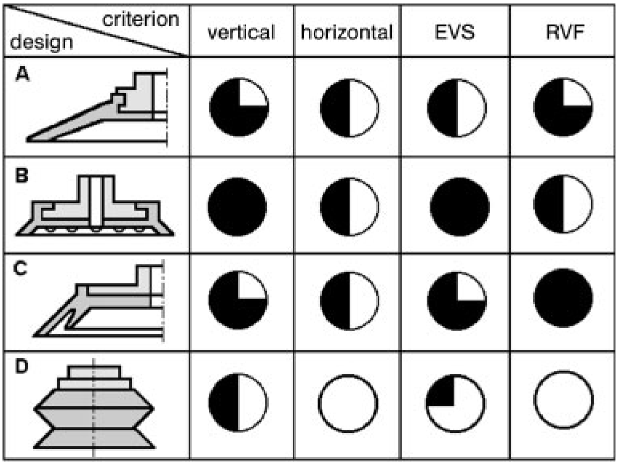
s stroke

Fig. 5.17: Evacuation phases of bellows

The evacuation of the bellows can be divided into two phases:

- The suction cup is positioned over the workpiece without any external forces acting on it.
- Vacuum is applied. The workpiece is lifted and, depending on gravitational forces and the underpressure, an equilibrium state is reached.

Figure 5.18 provides a rough overview of the typical characteristics which should be considered when selecting the most appropriate suction head. The criteria are related to the forces that can be transmitted when moving in a vertical and/or horizontal direction, the flexibility for a stroke at right angles, and the residual volume flow (leakage).



A flat suction cap
B ribbed suction cap
C double lip suction cup
D bellows

Fig. 5.18: Applications relevant properties of typical vacuum suction heads
full circle = very good
empty circle = very poor
vertical = transmittable vertical force
horizontal = transmittable horizontal force
EVS = elastic vertical stroke

Design A, although relatively simple, it delivers good results with respect to all criteria. The relatively large flexibility in the perpendicular direction with increasing vertical force is a limitation for its application only in rare cases.

Application: flat workpieces such as e.g. sheet metal boards, cartons, glass plates, plywood plates, coated flake boards.

The vertical forces acting on **Design B** can be very large because the suction cap volume remains constant even at high underpressure. The support ribs make the suction cup stiffer and hence tend to increase the retention force.

Application: thin metal sheets, parts with slightly rough (scaled) upper surfaces.

The double sealing in **Design C** results in a very small residual volume flow. However, the complex sealing system requires more space which limits the active diameter of the suction elements.

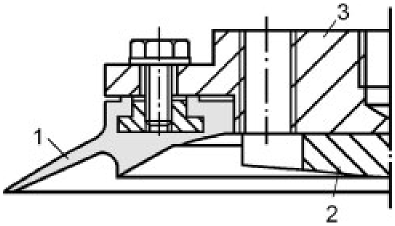
Application: Parts with pronounced structure on the upper surfaces, e.g. patterned glass, corrugated sheet metal, and natural stone.

Design D is characterized by low transmittance of vertical forces, insufficient geometrical stability and rather large elastic stroke in the vertical direction. This is a limiting factor for its application to many handling tasks.

Application: Delicate and/or uneven workpieces or when compensation for variations in surface profile is required, large area and flectional parts.

The following table gives a brief overview on the materials used for the manufacture of vacuum suction heads:

Material type	**Temperature in °C**	**Wear resistance**	**Stability against**		**Remarks**
			oil and grease	**weather, ozone**	
Nitrile rubber	– 40 to 70	good	very good	satisfactory	Flexible at low temperatures, water-resistant up to 70 °C
Silicone rubber	– 70 to 200	satisfactory	good	very good	Leaves no imprints if colourless, white, beige
Natural rubber	– 40 to 80	very good	not recommended	satisfactory	Durability, leaves no imprints if colourless
Polyurethane	– 25 to 80	very good	very good	very good	Durability, imprint free
Fluorine rubber	– 20 to 200	good	very good	very good	Highly resistant to chemicals, imprint free
Chloroprene	– 40 to 90	very good	good	good	Highly resistant to weather
PVC	– 20 to 85	very good	satisfactory	satisfactory	Very high durability
Ethylene / propylene / diene rubber	– 40 to 130	satisfactory	satisfactory	very good	Resistant to superheated stream and chemicals



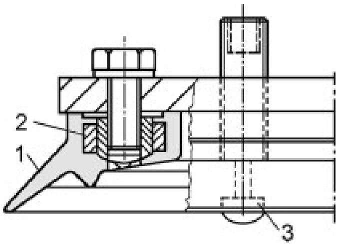
1 suction cap
2 separation element
3 carrier

Fig. 5.19: Suction head with separation element

Small design attributes can assist in making vacuum suction systems more effective. Figure 5.19 shows a suction cap with an integrated separation element. This produces shear stresses between the objects, e.g. thin metal sheets, and helps to separate thin oiled sheets with a thickness not exceeding 3 mm.

This reduces the probability of lifting more than one metal sheet. The prehended metal sheet settles in the centre of the suction cap. However, the buffer washer continues to move upwards whilst vacuum is still present. This has an arching effect on the metal sheet which is more pronounced only in the border area.

In order to ensure automatic activation of the vacuum on contact with the object it is necessary to install a sensor valve. One such example is shown in Figure 5.20. The sensor tip protrudes about 2 mm above the edge of the suction cap.



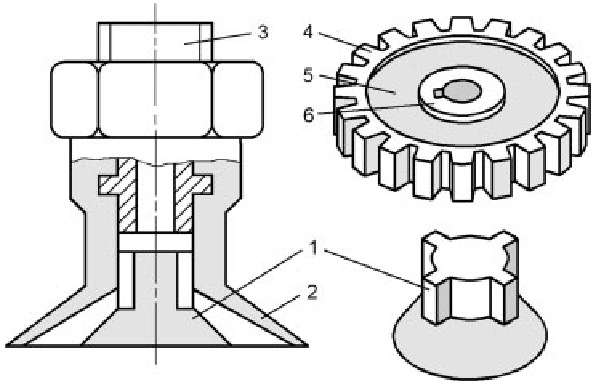
1 suction cap
2 fastener
3 sensor

Fig. 5.20: Suction cap with sensor valve

In certain cases there are no closed flat surfaces suitable for maintaining vacuum suction, for example in the case of a cogwheel with a central hole. Here, a ring surface suction cap with a plug in its centre, as shown schematically in Figure 5.21, is a suitable method. The plug is equipped with conducting channels for the passage of vacuum.

Special grippers have been designed for the prehension of pre-cut paper and foil parts. They are equipped with support ribs arranged in several concentric circles (Fig. 5.22). This ensures a uniform contact with such plane objects without the danger of deformation. Internal support elements are sometimes necessary when buckling or distorting of thin ($<$ 0.5 mm) steel or aluminium sheets must be avoided. This problem will now be considered in more detail.

With simple vacuum suction cups of the kind shown in Figure 5.18 a, the lifting of thin sheets with large areas can lead to blockage of the vacuum orifice as the sheet material is distorted. This results in a severe reduction in the effective gripping area as can be seen in Figure 5.23 c. In such cases the vacuum force must be better distributed over the object surface. A plurality of vacuum heads or single heads with the addition of support ribs or



1 rubber core
2 suction cap
3 threaded mounting
4 gripped object
5 object surface
6 inner cover ring surface

Fig. 5.21: Ring surface suction cap (*Sommer-automatic*)

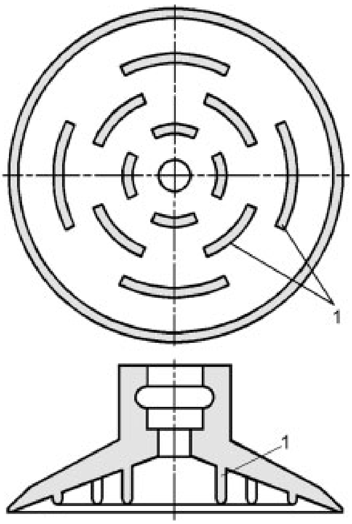


Fig. 5.22: Suction cap with support ribs
1 support rib

plates may serve to limit object deformation. Furthermore, as expression (3.70) suggests, the same prehension force can be achieved for a lower vacuum pressure given a larger prehension area.

Large gripping surfaces using lower levels of vacuum can also tolerate higher levels of leakage. Suction grippers are sometimes designed deliberately with this in mind, particularly where object forms vary widely.

Further information on prehension techniques using reduced vacuum can be found in references [5-7] and [5-8].

Figure 5.24 shows a gripper with distributed suction points. Multiple suction plates can be then combined into a composite gripper for use with larger area objects. However, such grippers are somewhat cumbersome.

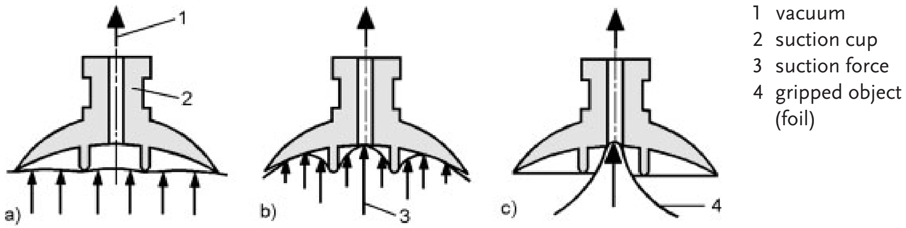


Fig. 5.23: Malfunction of a suction cup for prehension of unstable surface profiles
a) suction phase, b) formation of an internal sealing, c) malfunction

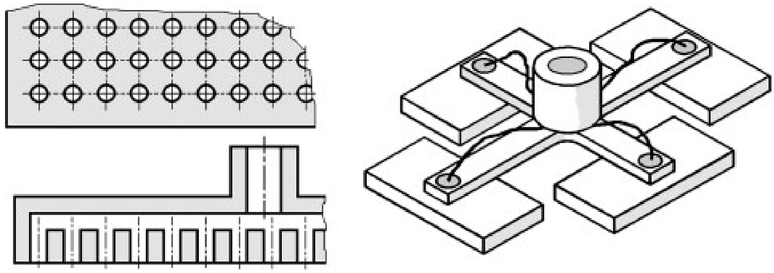


Fig. 5.24: Low pressure gripper (*Sommer-Automatic*)

Rapid motion can lead to displacement of the workpiece. In such cases the position can be secured by suitable constraints acting in the direction of acceleration. Two such examples are shown in Figure 5.25.

The exact position for prehension and subsequent manipulation is ensured for the gripper shown in Figure 5.25 a by a centring mandrel. Alternatively, this can be realized by a constraint supporting the workpiece during rapid horizontal motion.

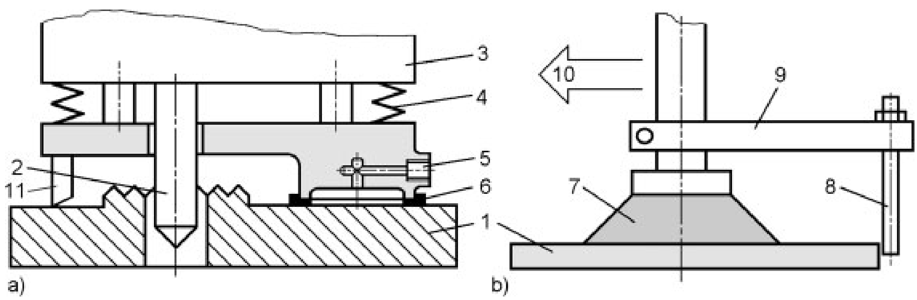


Fig. 5.25: Vacuum grippers with centring and constraint elements, respectively
a) suction plate gripper, b) suction cup gripper
1 object, 2 centring mandrel, 3 carrier, 4 return spring, 5 vacuum air connection, 6 seal, 7 suction cup, 8 stop pin (constraint), 9 holding arm, 10 acceleration direction, 11 support stop (constraint)

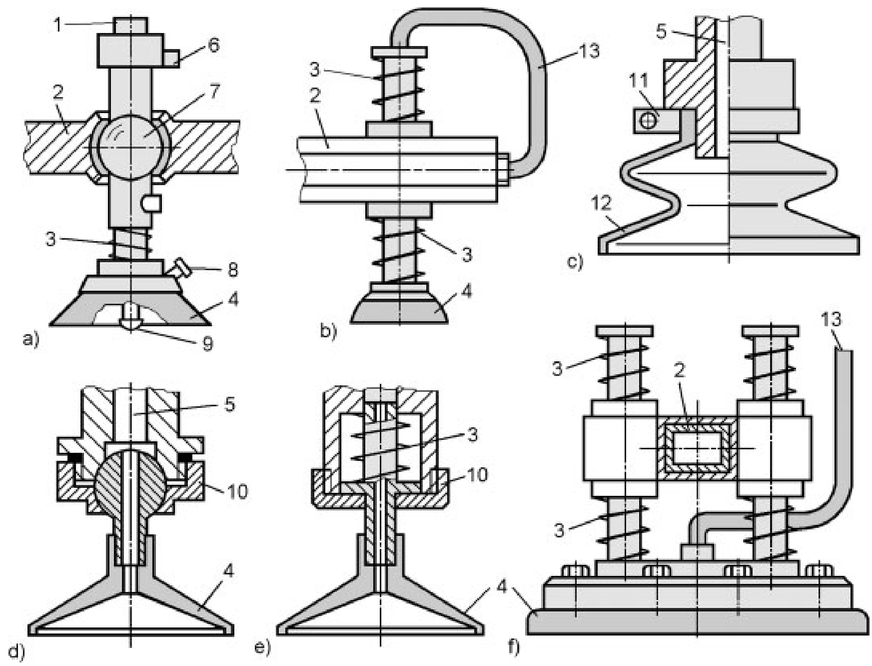


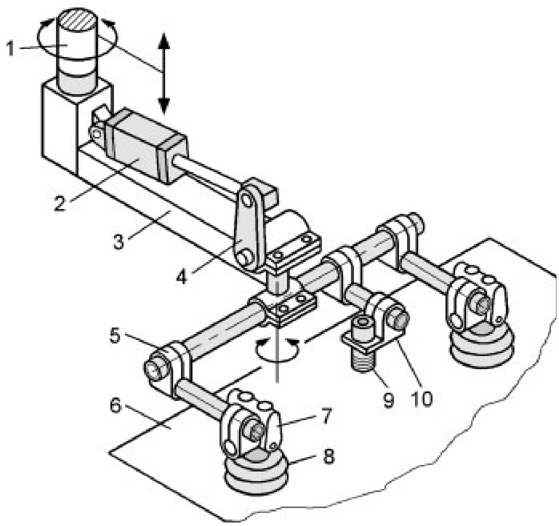
Fig. 5.26: Gripper attachments
a) moving-sphere attachment, b) double-sided springing, c) suction bellows with securing element, d) suction disc with securable universal joint, e) internally sprung suction disc, f) double guidance for large suction discs
1 compressed air connection, 2 cross brace, 3, return spring, 4 suction disc, 5 vacuum line, 6 Venturi nozzle, 7 angle error compensation, 8 manual exchange key, 9 contact vacuum switch, 10 receptacle nut, 11 securing ring, 12 suction bellows, 13 vacuum tube

The attachment of a vacuum suction head to the handling equipment can be realized in many different ways: adjustable-fixed, vertically sprung, double-sided sprung, angle-flexible – vertically sprung etc. Some examples are shown in Figure 5.26.

Sprung suspension ensures a light contact with the object surface and also helps protect against overstroke. Furthermore, load distribution during transport may be optimised. For large suction discs it is better to employ a double guide.

Many simple (non robotic) system are modular, containing extensive accessories for the attachment of grippers and sensors, allowing a degree of flexibility in what is otherwise “hard automation”. The example shown in Figure 5.27 possesses an integrated rotational axis. Traditional design comprises aluminium profiles or tubes, though in many cases aluminium has been replaced by lighter glass and carbon fibre composite materials in modern systems.

Good adaptation, e.g. to curved metal sheets, can be achieved if the suction heads are fixed to adjustable or ball-jointed retainers. One such example is presented in Figure 5.28. Once the suction cups are adjusted to the object, the universal joints are firmly clamped and cannot move.



1 coupling
2 pneumatic cylinder for the actuation of the rotary axis
3 beam
4 swivel mechanics
5 mountings
6 workpiece, sheet metal board
7 *Venturi* nozzle for vacuum generation
8 vacuum suction head
9 proximity switch
10 sensor mounting

Fig. 5.27: Gripper with integrated rotational axis (*Bilsing*)

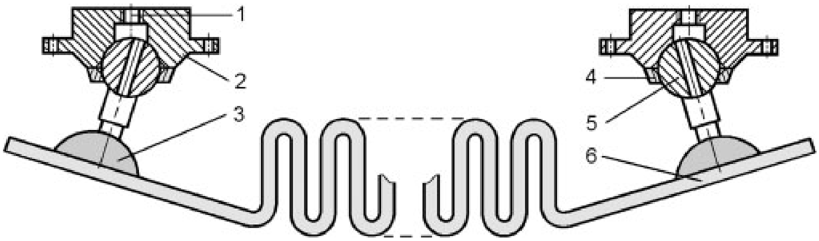
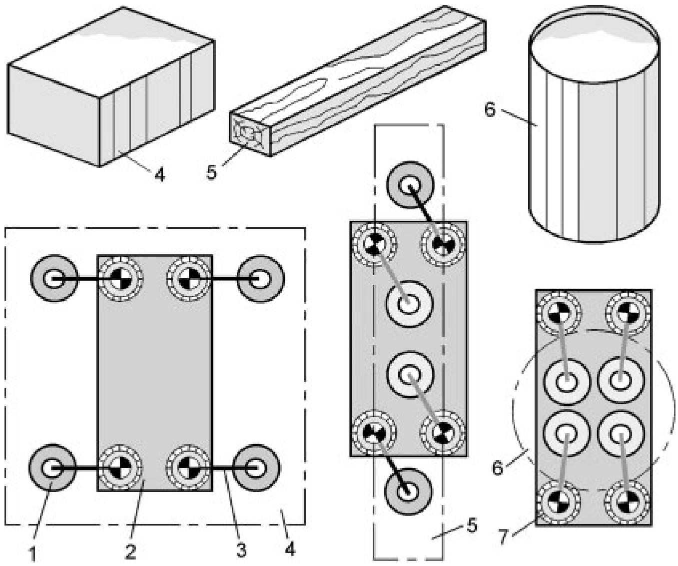


Fig. 5.28: Suction grippers fixed to a universal joint
1 vacuum connection, 2 mounting flange, 3 suction cup, 4 clamping collet, 5 ball pivot, 6 workpiece

In some cases the positional arrangement of the gripping heads is adjustable as shown schematically in Figure 5.29. The suction heads are fixed to moving arms, the endstop position of which can be manually changed in a relatively short time. This makes it possible to adjust the suction heads with the largest possible separation, within a minimum area or in line with each other, according to the available application or object surface profile.

A somewhat older idea for a customizable astrictive gripper is presented in Figure 5.30. The array consists of separate suction heads all capable of independent vertically displacement. Since the suction cups can adjust themselves automatically in 3 D space, the handling of profoundly varying surface profiles is possible.

Such manifestations are applicable to automated storage systems where a large variety of object shapes and sizes are to be expected. It is not necessary to activate every suction head for each prehension cycle and unused heads may simply be withdrawn. However,



1 section cap
2 baseplate, cross brace
3 pivot arm
4 gripped object
5 wooden beam
6 barrel
7 arm endstop

Fig. 5.29: Vacuum gripper principle with pivoting arms (*Schmalz*)

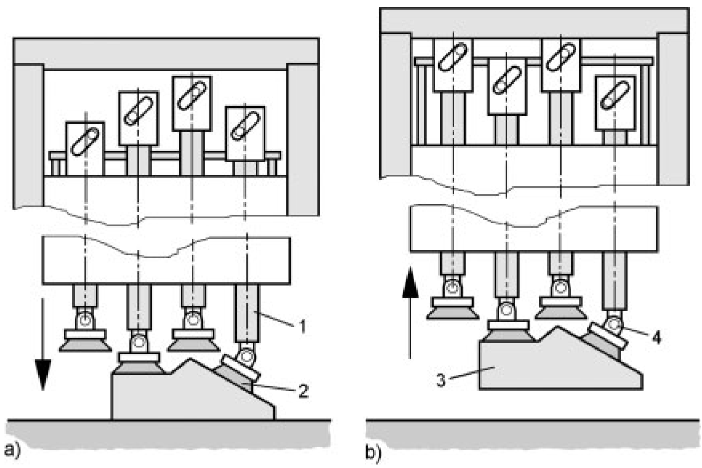


Fig. 5.30: Suction gripper with contour adjustment (*R. Tella, J. Birk, R. Kelley*)
a) moving of the suction caps towards the workpiece and attachment, b) lifting
1 guide rod, 2 suction cup, 3 workpiece, 4 cardan joint

either each suction cup must be controlled by a valve or capable of self sealing in the case of redundancy (see Fig. 5.9).

Finally it is worth considering the management of compressed air and the respective vacuum. In attaining prehension, air must be evacuated from the suction head as quickly as possible. Conversely, release time is dependant on air return.

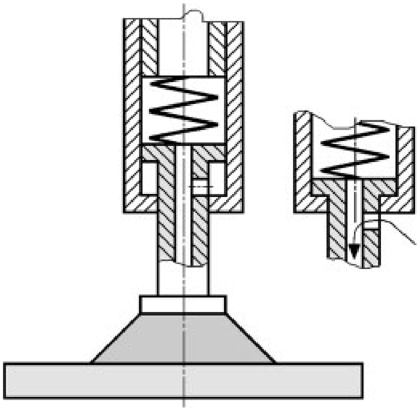
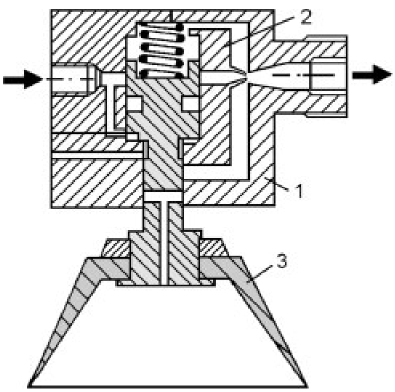


Fig. 5.31: Suction head with "shortcut opening" to atmosphere

These times are not only dependant on the volume of air in the suction heads. Pneumatic lines also contain a finite volume. For vacuum release, it is possible to build in "shortcut" to atmosphere as shown in Figure 5.31. During prehension of the workpiece the suction head is first (partially) evacuated. On withdrawal of the piston the vacuum is sealed in and the pump may be turned off. On release it is sufficient to slightly reduce the pressure in the cylinder so that the spring pushes the suction head downwards, allowing air in through the side opening. The response time is inversely proportional to the cross sectional area of the opening.

For rapid object prehension, the vacuum generator should be mounted as close to the suction head as possible. A sprung suction head is presented in Figure 5.32. The internal piston is shifted upon attachment so that the channels required for suction are connected. The Venturi nozzle is located in the same air flow path and produces the necessary vacuum. At the same time the compressed air maintains the piston in its upper position.

Correct vacuum management also helps improve efficiency. If one compares various ejectors, which can have one or several stages, it becomes clear that the efficiency η (p_u) deteriorates with the increasing vacuum demand. The efficiency is given by:



1 housing
2 nozzle
3 suction cup

Fig. 5.32: Suction head with automatic connection on attachment

$$\eta(p_u) = \frac{1}{1 + \frac{t\,(p_u) \cdot Q}{V}} \tag{5.12}$$

$t(p_u)$ evacuation time (in seconds) of a volume V for an underpressure p_u [bar]
Q air consumption of the vacuum nozzle [litres/second]
V volume that has to be evacuated [litres]

The efficiency dependency is shown in Figure 5.33.

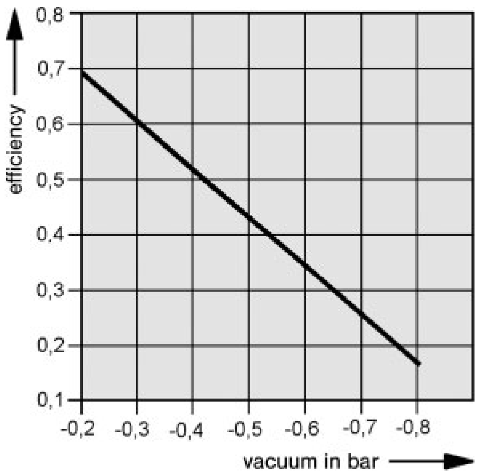
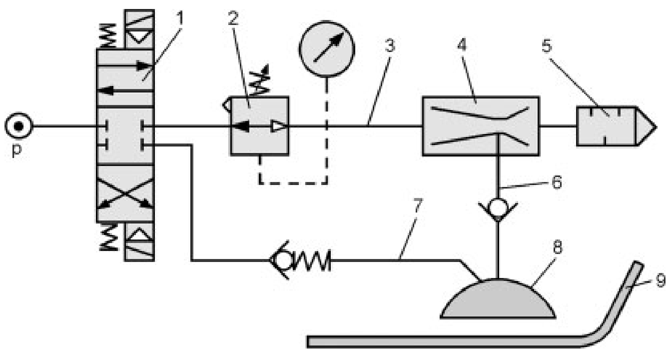


Fig. 5.33: Efficiency vs. vacuum at p_{nom}

The handling of sheet metal formed parts in the automobile industry often requires the use of large area grippers. The efficiency of such suction grippers depends essentially on the "vacuum management". Figure 5.34 shows a typical control cycle. It can be seen that the compressed air for vacuum generation is reconnected only if the underpresssure drops below a predetermined threshold value.



1 direction control valve
2 pressure adjustment
3 compressed air line
4 Venturi nozzle
5 absorbing duct
6 vacuum air line
7 blow-off line
8 vacuum suction head
9 workpiece

p compressed air

Fig. 5.34: Vacuum management for a large area gripper

Once the handling cycle is completed, e.g. within 20 seconds, the blow-off rejection system is activated for a short time. This is indispensable especially when handling fragile or very light parts.

Motor generated vacuum can be automatically turned off, by a pressure switch on the generator, when some vacuum limit value has been reached, thus saving energy. The vacuum control for a handling cycle of 20 seconds is presented in Figure 5.35. It can be seen from the diagram in Figure 5.35 b that the vacuum generator is briefly switched on every 5 seconds in order to maintain the limiting value. Release through blow-off is not always necessary. However, it does shorten the release time and provides a positive rejection of the object.

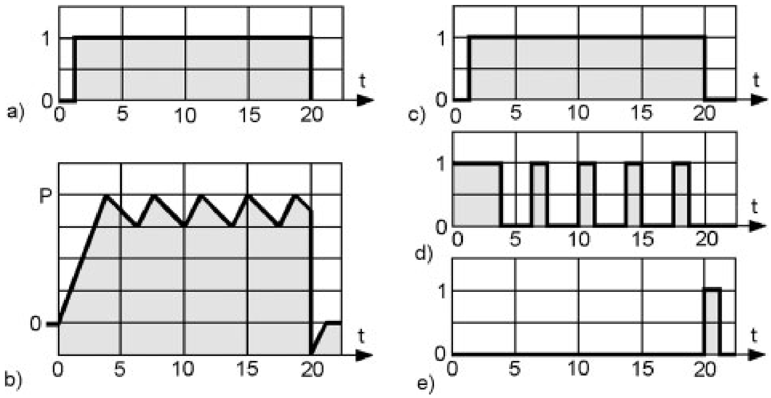


Fig. 5.35: Vacuum control for a gripper with vacuum generation by an electric pump
a) control signal for vacuum on/off, b) automatic readjustment of vacuum for leakage compensation, c) signal for object presence detection, d) control signal for vacuum readjustment, e) controlled blow-off
1 on, 0 off, *t* time in seconds

Figure 5.36 shows the design of a suction panel by which the user can determine the shape of the suction field. The vacuum prehension panel is built as a grid system of pegs.

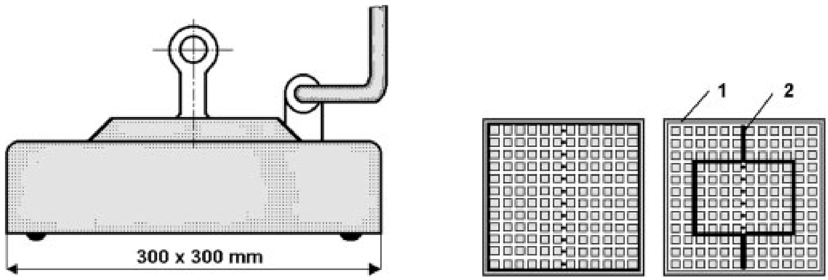


Fig. 5.36: Vacuum gripper employing a grid system (*HS Vacuum System*, Zürich)
1 suction plate with a grid of grooves, 2 rubber gasket

Depending on the available workpiece prehension surface the vacuum sealing band is inserted between the pegs in such a way that the resulting contour matches that of the workpiece surface. By this means holes and grooves in the workpiece may be avoided. Systems have been built capable of handling maximum loads up to 200 kg. It is also possible to combine several panels into larger gripper units.

Example: How many suction cups n are required in order to grasp a vehicle windshield, as depicted in Figure 5.37 and to pivot it from the horizontal into the vertical position?

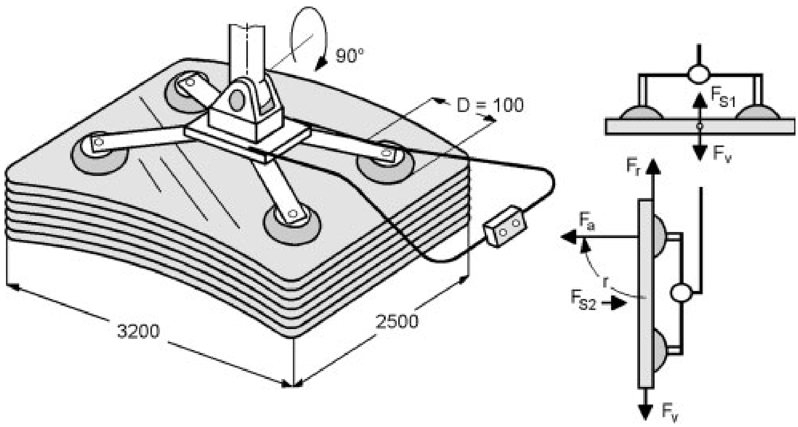


Fig. 5.37: Handling of an omnibus windshield
mass $m = 120$ kg, steady 90° tilt acceleration in $t = 3$s, suction cup/disc friction value $\mu = 0{,}7$

Solution: First of all the static loads will be calculated for the horizontal and vertical positions. Whilst the windshield remains horizontal, the vertical lifting force F_v corresponds to the force due to gravity.

$$F_v = m \cdot g = 120\,\text{kg} \cdot 9.81\,\text{m/s}^2 = 1177\,\text{N}$$

The required suction force F_{S1}, using a safety factor $S = 2$, is:

$$F_{S1} = F_v \cdot S = 1177\,\text{N} \cdot 2 = 2354\,\text{N}$$

Of course, the force due to acceleration of the robot against gravity must be added to this. Furthermore, if the lifting of the object in the horizontal position is rapid then it is also necessary to consider inertial forces. After rotation to the vertical position the friction force F_r must exceed the vertical force F_v, by some safety factor:

$$F_v \leq F_{S2} \cdot \mu = F_r \tag{5.13}$$

The vertical force F_v does not change when the end-effector is rotated and still amounts to $F_v = 1177$ N. The required suction force F_{S2} given $S = 2$ is:

$$F_{S2} = \frac{F_v \cdot S}{\mu} = \frac{1177\,\text{N} \cdot 2}{0.7} = 3363\ \text{N}$$

The suction force F_{S2} is larger than F_{S1} which is why it should be used as a basis for the following calculations. Furthermore, an additional dynamic force contribution is present during rotation. This contribution increases with the rotational speed. The maximum acceleration force resulting from the rotational motion occurs at the external suction cup row. Roughly speaking, the rotation path s is:

$$s = \frac{r \cdot \pi}{2} = 1.6\,\text{m} \cdot \frac{\pi}{2} = 2.51\ \text{m}$$

This gives for the acceleration a:

$$a = 2 \cdot \frac{s}{t^2} = 2 \cdot \frac{2.5\ \text{m}}{3^2 \cdot s^2} = 0.56\ \text{m/s}^2$$

The acceleration force F_a amounts to:

$$F_a = m \cdot a = 120\,\text{kg} \cdot 0.56\ \text{m/s}^2 = 67\ \text{N}$$

This allows us to calculate the total suction force F_{ges}:

$$F_{ges} = F_a + F_{S2} = 67\,\text{N} + 3363\,\text{N} = 3430\ \text{N}$$

Finally, the number n of the required suction cups must be calculated. If a suction cup diameter of 100 mm is selected and the applied vacuum is $p_u = -0.7$ bar (this corresponds to a vacuum of 70%), then Figure 5.38 gives a retention force of 397 N.

The 100 mm diameter corresponds to a physical dimension which is not fully utilised for prehension. In reality, the effective suction cup diameter is somewhat smaller (typically by a factor 0.85) than the nominal diameter. This factor can range from 0.6 to 0.9 and is a result of distortion due to underpressure, the flexibility (softness) etc. The theoretical holding forces calculated using the diagram are:

$$F = \frac{(D \cdot 0.85)^2 \cdot \pi}{4} \cdot p_u = \frac{(0.1 \cdot 0.85)^2 \cdot \pi}{4} \cdot 10^5 \cdot 0.7 = 397\ \text{N}$$

How many suction cups n must be used in the case of this example?

$$n = F_{ges}/F_S = 3430/397 = 8.6$$

Hence, 9 suction cups with a nominal diameter of $D = 100$ mm would be needed.

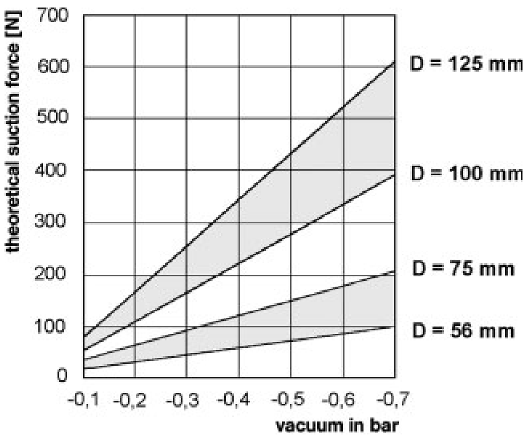
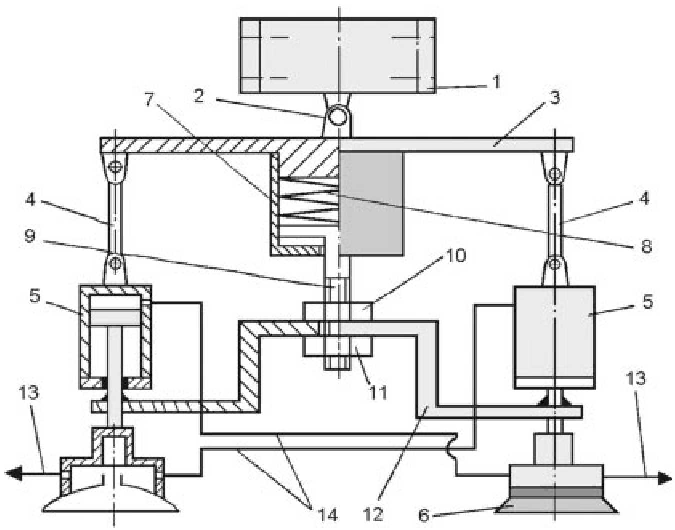


Fig. 5.38: Theoretical suction force as a function of vacuum
D suction cup diameter

Adaptive grippers, applicable in cases of uneven loads, are designed to adapt the gripping force to the load. This can be achieved by electro-mechanical or by fluidic means. Figure 5.39 shows such an adaptive vacuum gripper.

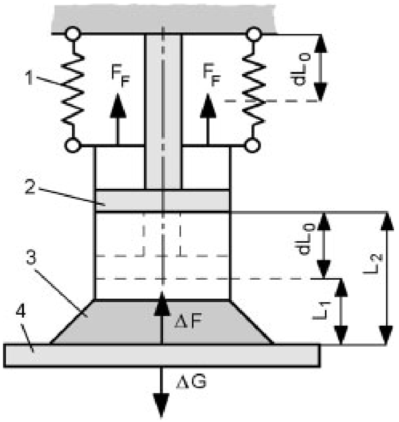
On contact with the object vacuum is connected to the suction plate allowing prehension of a defined nominal load. However, the suction plate is connected to a cylinder and if the object load exceeds the nominal load then the underpressure which occurs in the cylinder volume also exceeds the pressure created by the vacuum pump. This increases the vacuum beneath the suction plate so that the larger load remains adhered to the suction head.

The general mechanical principle of the adaptive gripper is shown in Figure 5.40. The adaptive part of the vacuum gripper becomes effective when the mass of the object in-



1 connection flange
2 joint bolt
3 cross beam
4 joint rod
5 pneumatic cylinder
6 Suction cap
7 spring chamber
8 tension spring
9 threaded bolt
10 nut
11 lock nut
12 carrying arm
13 vacuum air line
14 vacuum connection line

Fig. 5.39: Adaptive vacuum gripper [5–9]



1 tension spring
2 piston
3 suction cap
4 workpiece

Fig. 5.40: Principle of the adhesion gripper

creases by the amount ΔG, e.g. as a result of a momentary absorption of water (concrete panels and rainfall). Upon lifting of the gripper the tension spring is stretched by the length dL_o. At the same time the position of the suction plate remains unchanged.

The piston moves by the amount $dL_o = L_2 - L_1$. The vacuum in the cylinder and the suction chamber increases and the retention force ΔF is:

$$\Delta F = k_i \cdot A \cdot (p_2 - p_1) \tag{5.14}$$

k_i constant depending on suction cup material, interface, etc.
A area of suction contact
p_1, p_2 underpressure in the cylinder before and after load increase

The following condition must be satisfied in order to guarantee retention:

$$\Delta F + F_F \geq \Delta G \tag{5.15}$$

Here the spring force is given by

$$F_F = \lambda \cdot dL_0 \tag{5.16}$$

where λ is the spring constant which leads to:

$$k_i \cdot A \cdot (p_2 - p_1) + \lambda \cdot dL_0 \geq \Delta G \tag{5.17}$$

Since the volume of the cylinder remains unchanged, at constant temperature Boyle's law gives:

$$p_1 \cdot V_1 = p_2 \cdot V_2 \tag{5.18}$$

V_1, V_2 volume of the cylinder before and after increasing the load

Since the cross section of the cylinder is also constant:

$$p_1 \cdot L_1 = p_2 \cdot L_2 \tag{5.19}$$

Rearranging equation (5.17) yields:

$$k_1 \cdot A \cdot \left(\frac{p_1 \cdot L_1}{L_1 + dL_0} - p_1 \right) + \lambda \cdot dL_0 \geq \Delta G \tag{5.20}$$

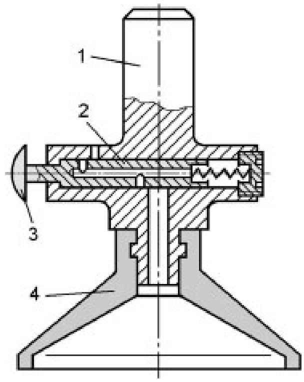
If the increase in load is now specified, the shift of the cylinder piston and the remaining dimensions of the gripper can be determined.

The following must be taken into account when connecting vacuum:
- Because of the small pressure difference the valve should ensure a good flow rate (higher flow rate than dictated by suction capacity alone).
- The underpressure switching valves must be suitable for negative pressure operation.
- The dimensioning of the valve should not be based on the connection thread of the suction nozzle. The important parameter is the maximum air consumption (flow rate).
- Materials used for suction cups include polyurethane (PUR), acrylonitrile butadiene (NBR) and silicone (SI) rubbers. Their resistance against various environmental effects differs (see also table on p. 185).

Criterion	**PUR**	**NBR**	**SI**
Temperature range	− 20 °C to + 60 °C	− 20 °C to + 89 °C	− 40 °C to + 200 °C
Lifetime	very high	good	satisfactory
Tensile strength	25 N/mm^2	16 N/mm^2	10 N/mm^2
Oil resistance	very good	very good	very good
Water resistance	very good	very good	conditionally resistant

5.1.3 Passive Suction Caps

The vacuum in passive suction caps is produced not by vacuum pumps or vacuum suction nozzles but simply by pressing a disk sucker having a relatively soft rim against a flat surface. Mechanical pressure can be applied by hand or machine. Thus the suckers need no further operational force and can also be applied to slightly curved surfaces. These grippers are not affected by failure in the power supply and can be considered as being secure, though leakage losses cannot be compensated for. The retention force which can be achieved through hand force, e.g. for a suction plate diameter of 63 mm and ground upper surface of the object, amounts to 140 N. Rocker arm suction lifters can accept loads of 25 to

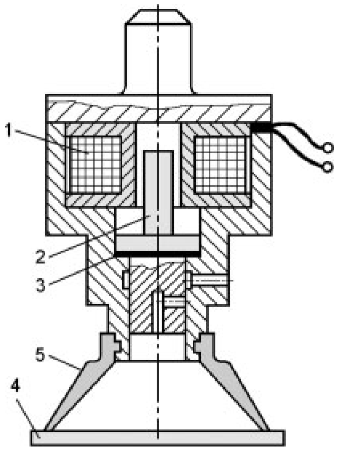


1 clamping pivot and carrier
2 manually operated slide damper
3 service button
4 disk sucker

Fig. 5.41: Principle of the adhesion sucker

100 kg with twofold safety. Figure 5.41 shows the constructional principle of an adhesion sucker. The object, e.g. a glass panel, is released by activating a slide damper.

Object release may be achieved remotely if an actuator to open an air inlet is included. For example, an electromagnet is employed in the design shown in Figure 5.42. Upon pressing the sucker against a surface an internal piston is pushed up allowing air to escape. The sucker is released by lifting the internal piston through electromagnetic force which in turn connects the air duct with atmosphere.

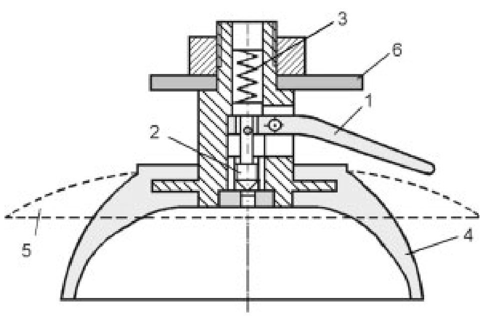


1 electromagnet
2 piston
3 sealing ring
4 object
5 sucker

Fig. 5.42: Adhesion sucker with electromagnetic release

Another design using a hand lever valve is shown in Figure 5.43. The underlying principle is the same as that shown in Figure 5.41. Pressing against the object produces vacuum and the valve cone is spring-loaded allowing manual release by allowing the re-entry of air.

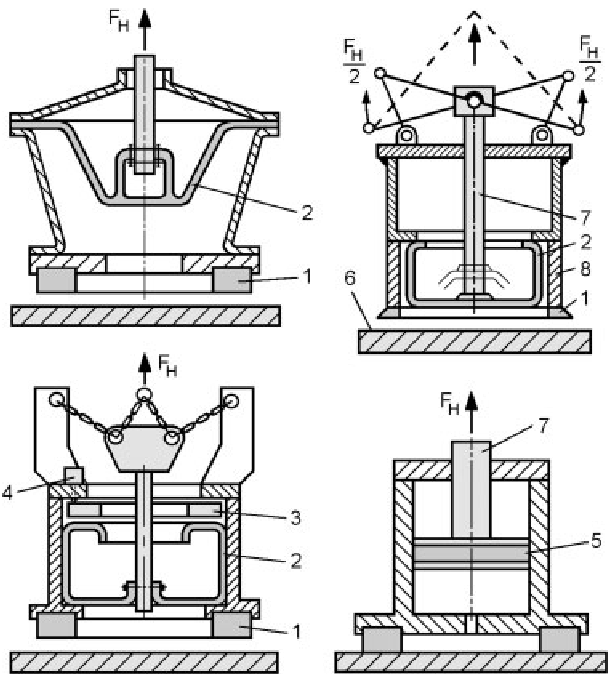
A selection of designs, whereby gavitational forces are utilised for vacuum generation, can be seen in Figure 5.44. Once the sucker makes contact with the object, a vertical force F_H is applied which leads to an increase in the volume beneath the sucker. The resulting



1 release lever
2 valve cone
3 return spring
4 sucker
5 sucker deformation during prehension
6 flange

Fig. 5.43: Adhesion sucker with valve lever

underpressure serves to retain the object. This state is reversed on removal of the load by deposition on a surface at the required destination. Such grippers are used in environments where object surfaces are very flat and non-porous and a power source is not readily available – delivery of glass panels etc.

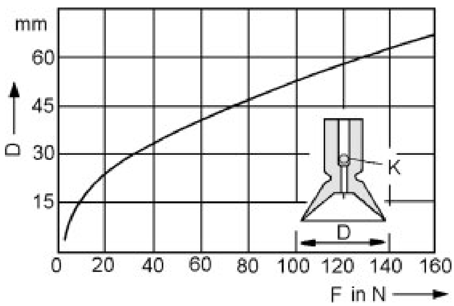


1 sealing ring or washer
2 rubber membrane
3 rubber ring
4 signal transmitter
5 piston
6 workpiece
7 piston rod
8 intermediate ring

F_H lifting force
m mass
g acceleration due to gravity

Fig. 5.44: Examples of suction through gravitational forces

In a first approximation one can estimate the achievable retention force from the diagram shown in Figure 5.45. The specifications are valid for flat or polished object surfaces with a roughness of $\leq 5\,\mu m$.



D effective suction cup diameter
F holding force
K spherical stopper

Fig. 5.45: Adhesion force using suckers

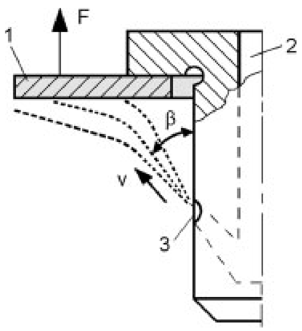
5.1.4
Air Jet Grippers

Air jet grippers retain an object with the help of air currents and vortices. For example, a workpiece is fed into a hole mechanically (locating pins, stops) but its prehension is not realized mechanically. The principle is demonstrated in Figure 5.46. The impact pressure of an air jet acting upon a surface produces the following force:

$$F = \frac{\varrho}{g} \cdot Q \cdot \nu \cdot \sin\beta \cdot 0.01 \qquad \text{in N} \tag{5.21}$$

Q volumetric air flow rate [l/s]
ν flow velocity [m/s]
β reflection angle in degree
ϱ air density [kg/m^3] ($\varrho = 1.199$ kg/m^3)
g acceleration of gravity [m/s^2]

Various grippers have been designed based on this physical principle and they are especially suited for very light components such as washers and flat pads. Figure 5.46 shows several potential design examples.



1 workpiece
2 air channel
3 nozzle

ν escape velocity

Fig. 5.46: Principle of the air jet gripper

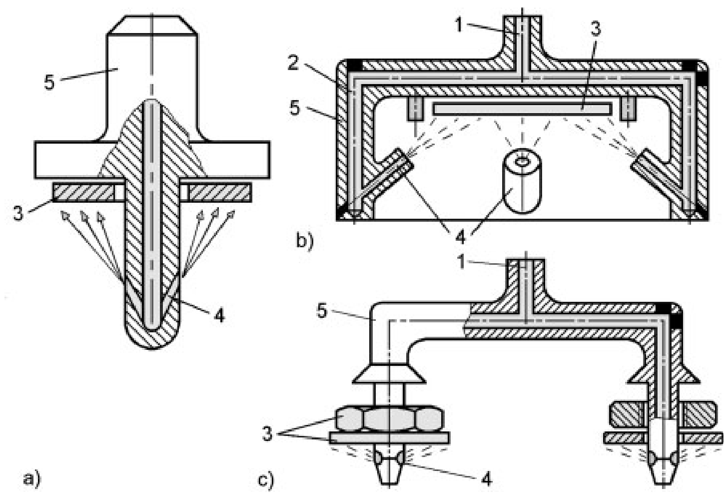
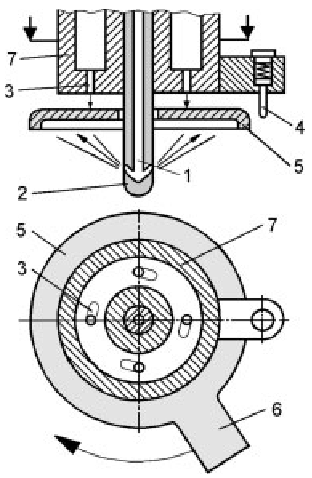


Fig. 5.47: Air jet gripper for screw plates and nuts
a) disk gripper, b) plate gripper, c) double gripper
1 compressed air supply, 2 compressed air channel, 3 assembly component, 4 nozzle, 5 carrier

It is also possible to design multiple grippers (Fig. 5.47 c), the grasping mandrels of which are preset in accordance with the separation characteristics of the objects to be lifted. The workpieces are released simply by turning off the compressed air. This type of gripper comprises little more than a plate and a nut and contains no moving parts.

The ring-shaped arrangement of the nozzles also allows the prehension of disks without a central hole (Fig. 5.47 b). Air jet grippers can even be used to perform orientation procedures. This is demonstrated by the example in Figure 5.48 where the workpiece possesses a nib which must be brought to a defined position (determined by the stop pin).



1 compressed air supply
2 gripping mandrel
3 inclined air nozzles
4 stop pin
5 workpiece
6 wokpiece nib
7 housing

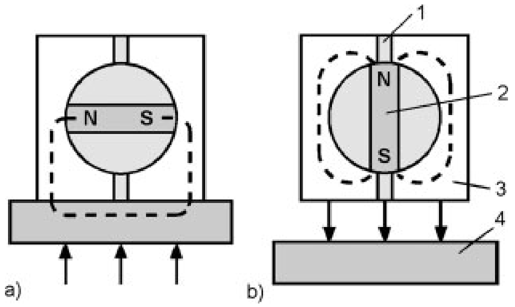
Fig. 5.48: Air jet gripper with orientation capability

This is achieved through the angular momentum transmitted to the workpiece through the inclined nozzle holes in the base of the housing. The part rotates virtually supported by air and is correctly positioned when the stop pin is reached. This orientation is a part of the automated mounting process.

5.2 Magnetoadhesion

5.2.1 Permanent Magnet Grippers

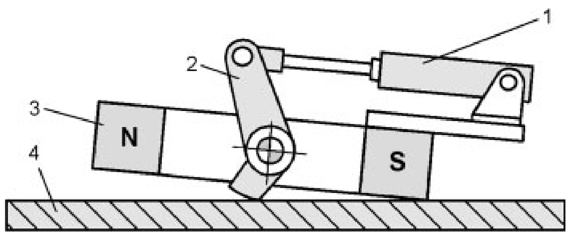
Like vacuum suction, magnetoadhesion may be implemented in both passive and active forms. A simple permanent magnet can be used to acquire magnetically susceptible (ferrous) objects. Specially designed magnets incorporate a mechanical switch mechanism for the purposes of flux diversion as shown in Figure 5.49. This way the flux path is merely diverted away from the gripping surface, but maintained through the magnet to prevent long term deterioration [5-10, 5-11]. For specially designed permanent magnets, typical retention pressures can be as high as 100 to 200 kN/m^2 [5-12].



1 non-magnetic material
2 permanent magnet
3 ferromagnetic housing
4 object

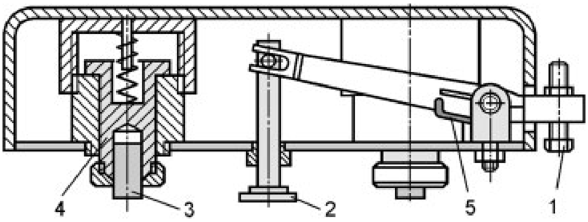
Fig. 5.49: Mechanical control of the magnetic flow
a) object prehension
b) object release

Another possibility is to achieve release by pushing the workpiece against the magnetic force. However, for this the gripper must be equipped with a special lever mechanism as in the design depicted in Figure 5.50. This leads to some intrinsic limitations: Due to the distance dependant magnetic field strength, the object is easily displaced during prehension and release. This is not true for electromagnetic grippers where the field is applied only after physical contact has been made.



1 pneumatic cylinder
2 lever
3 magnet
4 workpiece

Fig. 5.50: Principle of the permanent magnet gripper

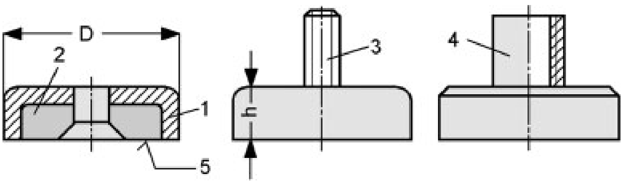


1 set screw for lever
2 ejection plate
3 permanent magnet
4 spring mounted guide
5 torsion spring

Fig. 5.51: Design of a permanent magnet gripper

Figure 5.51 shows the design of a permanent magnet gripper for use with pre-cut metal sheets. In this case the magnets are spring mounted so that they can be uniformly attached to the sheet metal. Since the magnetic field cannot be switched off, a lever element must be provided. A set screw limits the travel of the lever to which the ejection plate is mounted.

Figure 5.52 shows some prehension magnets (flat adhesion gripper) which are commercially available in different, mostly cylindrical, designs. Only one of the surfaces is arranged as a magnetically attracting surface. This type of design restricts the effective magnetic field area so that workpieces or components in the vicinity of the magnet are not affected.



1 soft iron pot
2 permanent magnet
3 threaded pin
4 threaded bush
5 adhesion surface

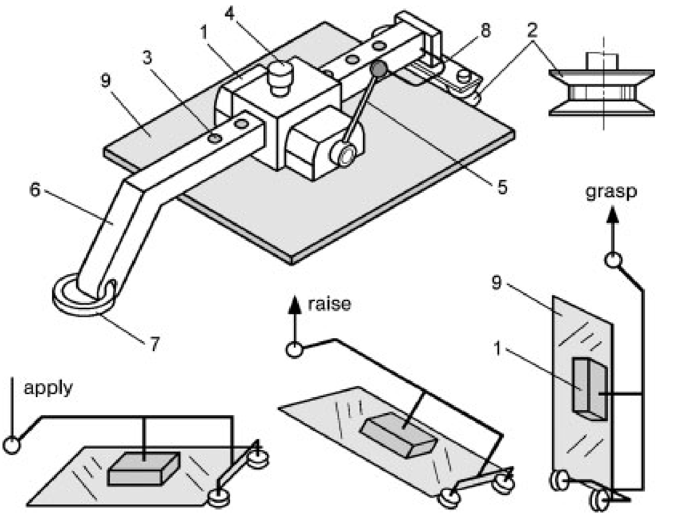
Fig. 5.52: Permanent magnet forms (*Welter*)

Gripper magnets maintain their magnetic force almost indefinitely. Deterioration of the magnetic field strength can occur in situations of high temperatures (over the Curie point of the magnetic material in question) and external (alternating) magnetic fields. Ceramic magnets are usable up to approximately 100 °C. The following table contains specifications for the achievable holding forces (gripper design according to Figure 5.53).

Diameter D in mm	Height h in mm	Adhering force in N
10	4,5	4
16	4,5	20
32	7,0	80
40	8,0	110
50	10,0	200
63	14	320
100	22	900

AlNiCo magnets can sustain temperatures of up to 450 °C. Rare earth magnets (Samarium-Cobalt, Neodymium-Boron, etc.) have an excellent magnetic field strength to weight ratio and can be operated up to approximately 200 °C. Most such magnets are sintered and require protective coating against corrosion. Further protection can be added in special cases (e.g. for use in the chemical industry). One major problem with simple magnetic grippers is that of remanence. Many magnetically susceptible materials remain slightly magnetised for a short while after field removal. A thin polymer coating on the magnetic surface of the gripper can reduce this problem significantly.

The gripper depicted in Figure 5.53 is used for hand guided grasping of flat steel sheets with subsequent raising and realignment in the vertical direction. With modern high power neodymium-iron magnets it is possible to achieve large forces even with an appreciable air gap, which is inevitable in many cases such as the handling of plastic coated sheets.



1 permanent magnet
2 support roller
3 cocking hole
4 index bolt
5 actuating lever for magnet switching
6 lifting arm
7 securing lug
8 service handle
9 steel sheet board

Fig. 5.53: Magnet load cross-beam for chain hoists and manipulators

The magnets are extremely compact, low-maintenance and well suited for flat materials, rods and iron tubes. In the example given in Figure 5.53 the magnet can be moved along the lever arm. The sheet is made to lie against support rollers which accept the weight during pivoting.

The permanent magnet is switchable so that the steel sheets cannot move as the magnet approaches. The following table contains some technical data of permanent neodymium-iron magnets:

External dimensions [mm]	Height [mm]	Cohesive release force [kN]	Nominal holding force [kN] flat parts	Nominal holding force [kN] round parts	Deadweight [kg]
180 × 95	100	3	1	0.5	12
330 × 95	100	7.5	2.5	1.25	16
245 × 120	120	15	5	2.5	26

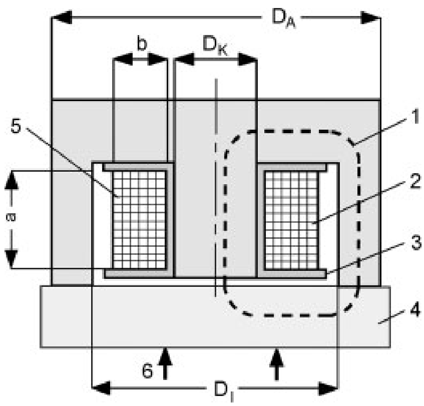
5.2.2 Electromagnetic Grippers

In addition to permanent magnets, a magnetic field can be electrically generated, as shown in Figure 5.54. Normally made from one or more coils wound on cores of high magnetic permeability, prehension force F may (in its simplest form) be calculated using conventional electromagnetic formulae (5.22):

$$F = B \cdot I \cdot l \quad [\mathrm{N}] \tag{5.22}$$

where:

B magnetic flux density [T]
I current through conductor [A]
l length of conductor [m]



1 magnetic flux path
2 coil with n-windings
3 coil former
4 ferromagnetic object
5 winding cross-sections a · b
6 prehension force

Fig. 5.54: Electromagnetic gripper

The flux density B can be calculated from expression (5.23):

$$B = \mu_0 \cdot \mu_r \cdot H = \frac{\Phi}{A} \tag{5.23}$$

where:

μ_o permeability of free space [$4\pi \cdot 10^{-7}$ H/m]
μ_r relative permeability
H magnetic field strength [amps/metre]
Φ magnetic flux [Weber]
A_m area of magnetic path [m^2]

Equation (5.23) assumes that the relationship between B and H is linear. In reality considerable hysteresis is likely to exists, particularly if the magnetic core is driven into saturation. In such cases, the design of an electromagnet would rely on the use of exact data extracted from characteristic curves for the core material used. This book is intended only to illustrate the means by which the magnitude of gripping forces can be estimated. Readers who are specifically interested in inductor and electromagnet design should consult more specialised texts.

From formula (5.24), the magnetic field strength H can be calculated:

$$H = \frac{N \cdot I}{p} \tag{5.24}$$

where:
N number of coil windings
p magnetic path length (m)

Equations (5.22) to (5.24) can be combined to give (5.25)

$$F = \frac{\mu_0 \cdot \mu_r \cdot N^2 \cdot I^2 \cdot l}{2p} \tag{5.25}$$

Dividing by the area A, (which represents the whole interface area including those parts, directly below the coil windings, which do not include the magnetic path) gives an expression for retention pressure (5.26):

$$\sigma = \frac{\mu \cdot N^2 \cdot I^2 \cdot l}{2p \cdot A} \tag{5.26}$$

where the product $\mu_o \, \mu_r$ has been abbreviated simply to μ.

However, this is only applicable directly in cases where the relative permeability of the object material is exactly the same as that of the core. This is often assumed to be the case when manufacturer's technical data refer to the maximum available electromagnetic force. Whilst certain permalloys can have relative permeability's as high as 70,000, more realistic object materials such as iron have relative permeability's typically in the region of 1000 [5-13]. Where the permeability's of core and object are different, the magnetic circuit must be modelled in a similar manner to electrical circuits, but using magnetic reluctance (analogous to electrical resistance). Expression (5.26) represents the maximum available retention pressure and does not take into account any inhomogeneities in object permeability or surface profile.

An example of a realistic magnetization curve (magnetic flux density B against magnetic field strength H) for cast iron is shown in Figure 5.55.

Example: A 5 cm diameter electromagnetic gripper consists of a 200 turn coil of average turns length 6 cm, mounted on a high permeability core ($\mu_r = 2000$) of magnetic path length 12 cm (including 2 cm through the object). If, operated from a 24 V DC supply a current of 1 Amp is drawn, calculate the maximum retention force and that obtainable when the gripper is used with an iron object having a relative permeability of 1000.

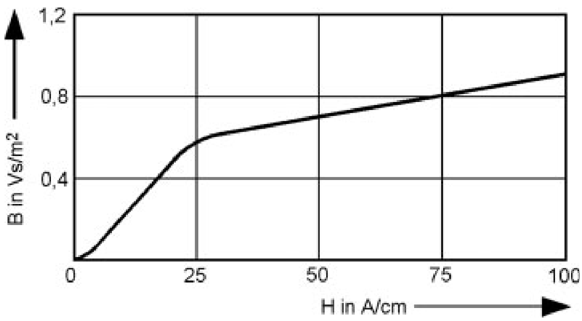


Fig. 5.55: Magnetization curve for cast iron

From (3.93):

$$F = \frac{4 \cdot \pi \cdot 10^{-7} \cdot 2 \cdot 10^3 \cdot 1^2 \cdot 6 \cdot 10^{-2} \cdot 2 \cdot 10^4}{2 \cdot 12 \cdot 10^{-2}} = 25 \text{ N}$$

However, if 2 cm of this total magnetic path has $\mu_r = 1000$ and only 10 cm where $\mu_r = 2000$ then the reduction in holding force will be in the ratio of the reluctances:

$$F' = \frac{R_1}{R_2} \cdot F \tag{5.27}$$

whereby the magnetic reluctance is:

$$R = \frac{p}{\mu \cdot A} \tag{5.28}$$

Assuming the magnetic path areas are the same (which may not always be the case):

$$F' = \frac{10 \cdot 2000 + 2 \cdot 1000}{12 \cdot 2000} F = 0.92 \text{f} = 23 \text{ N}$$

Steady state power consumption $P = I^2 R$

$$P = I^2 \cdot R \tag{5.29}$$

Substituting (3.94) and (3.97) into (3.91) gives (3.98)

$$Q = \frac{P}{\sigma} = \frac{2R \cdot p \cdot A}{\mu \cdot N^2 \cdot l} \tag{5.30}$$

It is interesting to note that Q has the same dimensions as it did with the vacuum suction technique. Though Q no longer exactly represents volumetric flow rate in the fluid sense, it is still applicable as a figure of relative merit for gripper performance in that it is a measure of the ratio of power consumption to retention pressure.

For a magnetic core cross sectional area given by A the total magnetic flux ϕ can be similarly derived as in equation (5.31):

$$\phi = B \cdot A = \frac{\mu \cdot N^2 \cdot I \cdot A}{p} \tag{5.31}$$

This gives an expression (5.32) for the coil inductance L

$$L = \frac{w \cdot \phi}{I} = \frac{\mu \cdot N^2 \cdot A}{p} \tag{5.32}$$

and electrical resistance for a conductor of resistivity ϱ and cross sectional area A_c

$$R = \frac{\varrho \cdot L \cdot N}{A_c} \tag{5.33}$$

From expressions (5.32) and (5.33) we can calculate a time constant τ for the gripper:

$$\tau = \frac{L}{R} \tag{5.34}$$

The current flow I through the electromagnetic gripper, following switch on is given by equation (5.35):

$$I = I_s\,(1 - e^{-t/\tau}) \tag{5.35}$$

where I_s is the final steady state value which is responsible for the power consumption as given in (5.29). This results in a flow rate Q following the same pattern (5.36):

$$Q = Q_s \cdot (1 - e^{-t/\tau}) \tag{5.36}$$

The decay current and corresponding flow rates are given by (5.37) and (5.38) respectively. To protect the drive circuit from the effects of large back-EMF's a flywheel diode may be required across the inductance. To maintain a relatively short time constant an additional resistance must be included in series with the flywheel diode.

$$I = I_S \cdot e^{-t/\tau} \tag{5.37}$$

$$Q = Q_S \cdot e^{-t/\tau} \tag{5.38}$$

From equation (5.25) increasing the current flow can be seen to be the simplest way of improving the holding force. However, this will also result in proportionally larger power dissipation according to (5.29). Increasing the number of turns will also improve the gripping force, but at the expense of a higher inductance (5.32) and consequently longer time constant (5.34). From formula (5.33) N can be seen to be directly proportional to R. Also, the greater the number of turns, the smaller the individual conductor cross sectional area for a given coil size. This in itself will limit the allowable current but is often more effective than simply increasing the current to a coil of fewer turns. In practice, the limiting factor in this respect will be expense. Inductors of many turns simply cost more to manufacture than those having fewer.

Continuing with this example, one obtains a feeling for what the "flow rate" Q really means. The time constant τ should be further investigated when an iron object is acquired by the gripper. The electrical resistance of the coil is $R = U/I = 24\,\Omega$. According to equation (5.29), power $P = I^2 \cdot R = 24\,\mathrm{W}$ for a gripper with an effective prehension surface of $A = \pi \cdot r^2 = 19{,}6\,\mathrm{cm}^2$ and the prehension pressure $\sigma = 23/(19{,}6 \cdot 10^{-4}) = 11735$ $\mathrm{N/m}^2$. Dividing power by pressure gives $Q \approx 24/11735 \approx 0{,}002\ \mathrm{m}^3/\mathrm{s}$. The maximum inductance can now be calculated according to (5.32):

$$L = \frac{4 \cdot \pi \cdot 10^{-7} \cdot 2 \cdot 10^3 \cdot 4 \cdot 10^4 \cdot 19 \cdot 6 \cdot 10^{-4}}{12 \cdot 10^{-2}} = 1.64\ H$$

If the gripper now comes into contact with an iron object then the inductance will, according to (5.27), be:

$$L = 0.92 \cdot 1.64 = 1.51\ H$$

And consequently, the time constant τ from (5.34);

$$\tau = \frac{1.51}{24} = 0.063\ s$$

This means that 63% of the electrical current, and hence magnetic flux, will have built up 0.063 seconds after switch on. Similarly, 0.063 seconds will be required before 63% of the flux will have decayed after switch off. This means gripping and release times will be in terms of several seconds.

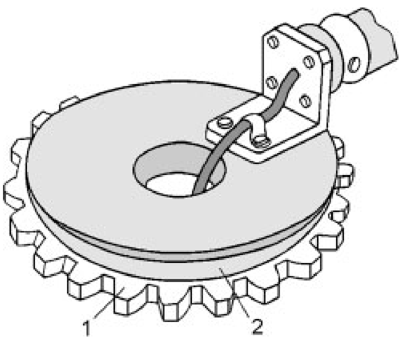
In circumstances where a larger number of windings are used, the consequent larger inductance will give an increase in time constant. This is not usually a problem for many industrial electromagnet applications such as ferrous scrap metal handling. However, such time delays are often unacceptable in pick and place, assembly etc. As in the permanent magnet case, a thin (several hundred micrometer) polymer coating on the magnetic surface of the gripper can help expedite things. More explicit design details for electromagnetic gripper can be found elsewhere [5-14, 5-15].

Electromagnets may be operated from either direct or alternating current. In the case of the former, unless the cores are laminated, some residual magnetisation may remain in the object after release. Where alternating current supplies are used, the direction of the magnetic field will reverse in time with the current passing though the coil, though from (5.25) the retention force can be seen to be the same regardless of the direction of the current. Provided the frequency of the supply is not so low that the object has time to become detached from the gripper before the next magnetising half cycle, the holding force will be maintained. However, when using alternating currents the likelihood of residual magnetic polarisationis minimised and the object acquisition and release time responses will decrease with increasing frequency. Unfortunately, at higher frequencies, skin effect and mutual inductances between winding layers must be taken into account. These effects reduce the attainable magnetic field whilst increasing the impedance of the coil [5-16].

The advantages of electromagnetic grippers are:
- Simple compact construction with no moving parts.
- Uncomplicated energy supply and control (none with permanent magnets).
- Relatively independent of object size and gravitational centre.
- No power losses due to friction.
- Usable with a wide range of object sizes and shapes.

The disadvantages of electromagnetic grippers are:
- Usable only with ferrous materials (Iron, Nickel, Cobalt).
- Extended release times due to magnetic remanence. This can also lead to the collection of fine magnetic particles and dust over prolonged time.
- As with most astrictive techniques, failure of the power supply leads to (almost) immediate object release.
- Gripper weight directly dependant on required prehension force.
- Unlike with impactive techniques centring of the object within the gripper as part of the prehension process is not possible.
- Due to permeating effects of the magnetic field, separation of thin sheet objects from one another is difficult.
- When driven from DC supplies the object can become slightly magnetised. This can result in added costs should it be necessary to demagnetise parts at a later stage.

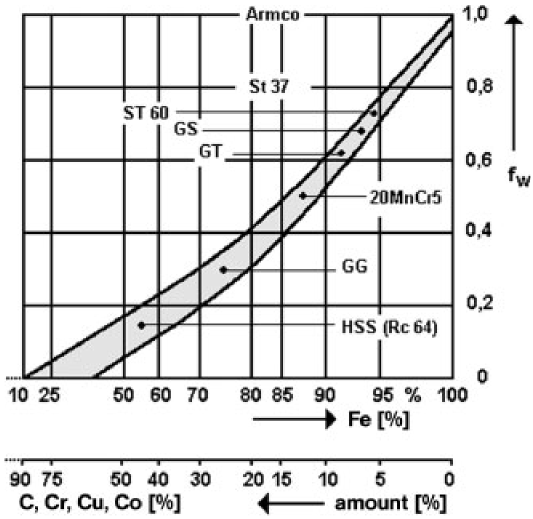
The following design example demonstrates a simple gripper intended for the handling of cog wheels depicted in Figure 5.56. The realisable prehension force depends on a number of factors:
- Size of the contact area between gripper and object.
- Material properties.
- Roughness at the interface (air gap).
- Percentage of the prehension area effectively used.
- Magnetic field strength of the electromagnet.



1 object
2 electromagnet

Fig. 5.56: Electromagnetic gripper for handling cog wheels [5-17]

Objects having different magnetisation curves will experience different prehension forces with the same gripper. The magnetic saturation of a material largely determines the upper limit for prehension force. The graph shown in Figure 5.57 provides an overview. Pure iron has a correction factor $f_w = 1$. Steel also contains certain amounts of carbon, Chromium, Nickel, Manganese, Molybdenum, Copper etc., all of which serve to increase the magnetic reluctance. In addition, hardened metals tend to exhibit poorer magnetoadhesion characteristics due to changes in the metals crystal structure.



f_w correction factor
GG cast iron
GT wrought iron
GS cast steel
St steel

Fig. 5.57: Dependence of magneto-adhesive force on material

A precise geometrical design of the magnet pole shoe makes the handling of workpieces with greatly differing shapes and sizes possible. Figure 5.58 shows two such examples where the electromagnet is spring mounted. Upon energising the electromagnet the reception position is secured magnetically. The spring loading helps facilitate object release.

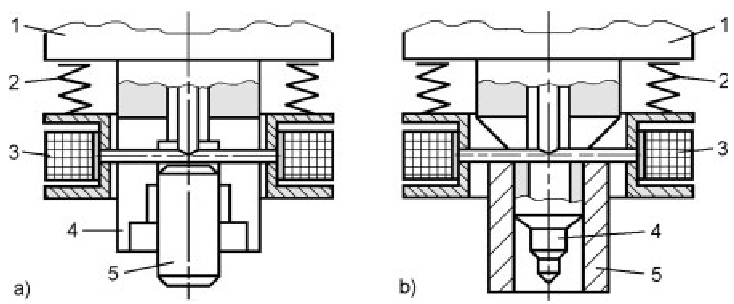


Fig. 5.58: Electromagnetic gripper with adapted workpiece receivers
a) external grip, b) internal grip
1 gripper flange, 2 return spring, 3 magnet coil, 4 workpiece receiver, 5 workpiece

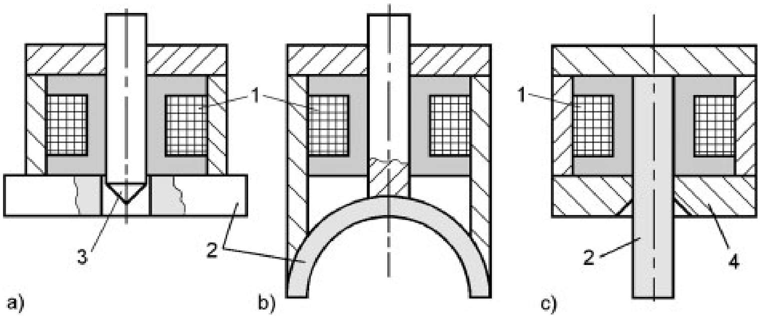
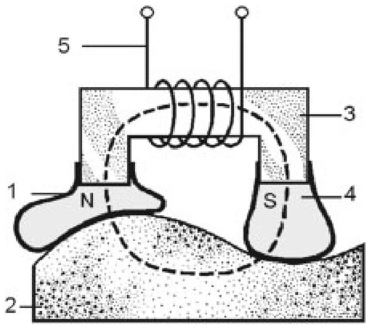


Fig. 5.59: Electromagnetic gripper for special applications
a) centring spike, b) pole shoe for curved objects, c) pivot gripper
1 coil, 2 workpiece, 3 centring pin, 4 guide plate

Figure 5.59 shows some further examples for adaptation of the pole shoe to the object. The gripping surface is made from a magnetically susceptible material. The sizes of the holes and apertures are small and have no significant affect on prehension force.

Many ideas for shape adaptive grippers where developed during the 1970s. The magnetic powder gripper in Figure 5.60 has been used for the handling of cast iron parts. The jaws consist of polymer sacks containing either magnetic powder or magnetorheological fluid. This allows magnetic flux to pass through the sacks without an excessive number of air gaps as a result of the objects rough or uneven surface. One dissadvantage is the danger of damage to the elastic cladding by sharp points or edges.



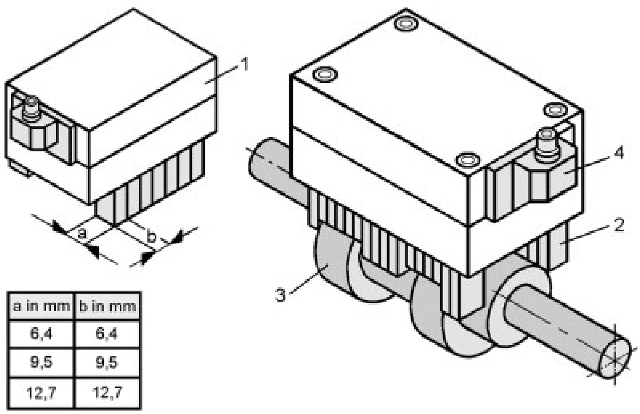
1 elastomeric cladding
2 object
3 magnetic core (yoke)
4 iron powder or magnetorheological fluid
5 connection line

N north pole
S south pole

Fig. 5.60: Magnetic powder gripper (*Shinko-Electric*, Japan)

Flexibility of the gripper shown in Figure 5.61 is achieved through the splitting of the pole shoes into separate movable elements. On contact with the object they adapt themselves to the objects profile. As the magnetic field is applied not only is a prehension force generated but the metal elements remain fixed in place. Such a prehension strategy is ideally suited to rigid objects of 3D topology.

Magnetic grippers can also be designed to hold several different objects simultaneously and the variety of possibilities is immense. Further gripper designs for both robotic and manual handling can be found in [5-18].



a in mm	b in mm
6,4	6,4
9,5	9,5
12,7	12,7

1 stainless steel housing
2 laminate pole shoes
3 object
4 power connection

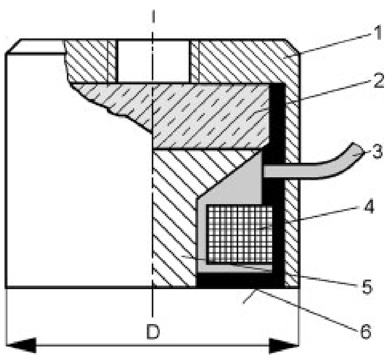
Fig. 5.61: Profile magnetic gripper (*Knight*)

Most small electromagnets are designed for use with either 12 V (automobile) or 24 V (industrial standard) power supplies. When used as a magnetoadhesive gripper such electric supplies can be augmented by battery back-up ensuring maintenance of the holding force in cases of sudden power failure.

5.2.3 Hybrid Electromagnetic Grippers

The combination of permanent magnets with electromagnets is widely used (for example hybrid stepper motors). Magnetoadhesors can also benefit from this feature as shown in Figure 5.62.

These are systems with an open magnetic circuit intended for particularly long term retention of ferromagnetic workpieces. In the activated state, an exciter winding neutralizes the permanent magnetic field resulting in object release. In order to avoid residual magnetization of the object, a counter-field during deposition may be electrically generated.



1 housing, bell
2 permanent magnet
3 connection line
4 exciter winding
5 soft iron core
6 magnetoadhesive surface

D 20 to 150 mm

Fig. 5.62: Hybrid magnetoadhesive gripper (*Binder*)

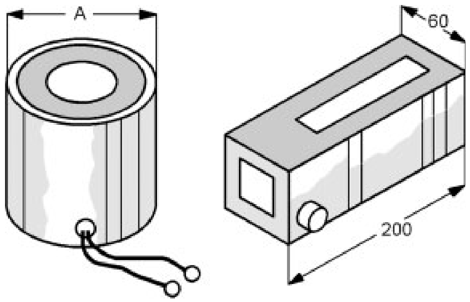


Fig. 5.63: Design examples hybrid magnetoadhesors
A diameter 20...150 mm

Diameter A in mm	20	35	55	70	90	105	150
Nominal adhering force in N	40	160	420	720	1200	1600	3500

The adhesion force remains unchanged in cases of power failure. The neutralization is rarely perfect and the residual adhesion forces after activation are less than 3% of the nominal adhesion force. Both cylindrical and cuboid designs are commercially available, as can be seen in Figure 5.63.

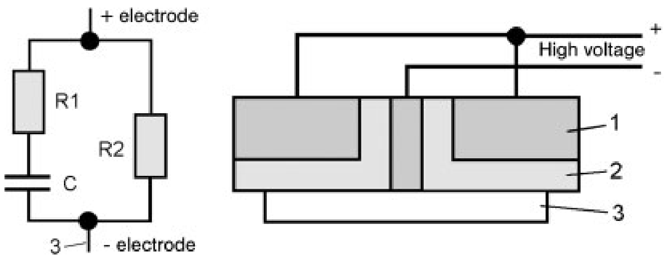
5.4 Electroadhesion

Electrostatic fields, like their magnetic counterparts, can be used to provide an astrictive force, known as electroadhesion [5-19]. Though in all cases this is not as easily quantified as with the magnetic devices, some calculations can be carried out which will give an idea of the scale of the forces involved. The electrostatic equivalent to the simple pneumatic suction cup and the permanent magnet is the electret [5-20]. Though electrets exhibit permanent electrostatic force, these forces are normally too small for practical use in prehension and so will not be considered here. The simplest active method relies on the force produced within a dielectric which is subjected to an external electric field.

Since the 1990s, and particularly in USA and Japan, electroadhesion has seen considerable interest for the retention of semiconductor wafers during processing (*electrostatic chucks*). Electroadhesion has two significant advantages over vacuum suction. The first is that it may be used with wafers which have already been partly machined and contain holes. The second is its ability to operate in vacuum environments – something of increasing interest among chip manufacturers.

5.4.1 Electroadhesive Prehension of Electrical Conductors

Figure 5.64 shows a typical example and its equivalent electrical circuit. The applied potential (EHT) is normally in the range of several thousand volts. From the point of view of



1 electrodes
2 dielectric
3 electrically conducting object

Fig. 5.64: Cross-section of an electrostatic gripper

maximising the available force, the arrangement shown in Figure 5.64 is essentially a single capacitor. In this case the object itself is connected directly to one side of the supply, through the grippers central electrode, which of course should be earthed for safety reasons.

Equation (5.39) is derived from basic electrostatic theory for a simple planar capacitor [5-21] from which the basic equation for capacitance (5.40) can also be derived [5-22]. The relationship between the electric field strength E and the electric displacement D is given by:

$$D = \varepsilon_0 \cdot E + P_m = \varepsilon_0 (1 + \chi_e) \cdot E = \varepsilon \cdot E \qquad (5.39)$$

D electric displacement [A · s/m2]
E electric field strength [V/m]
χ_e $\chi_e = \varepsilon_0 - 1$; Electric susceptibility
P_m electric polarisation

As in its electromagnetic counterpart, in equation (5.40) ε represents the permittivity (the product of free space permittivity ε_0 multiplied by the dielectric constant ε_r).

$$\text{Capacitance } C = \varepsilon \cdot \frac{A}{d} = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \qquad \text{[Farad]} \qquad (5.40)$$

A interface between gripper and object [m^2]
d dielectric thickness [m]

Using the physical formula, energy $e = {}^1/_2 CV^2$ and rearranging $e = F \cdot d$ gives the retention force F as in equation (5.41)

$$F = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A \cdot V^2}{2 \cdot d^2} \qquad (5.41)$$

V applied potential [Volts]

Re-arranging equations (5.40) and (5.41) and dividing by the gripper to object contact area A, gives the retention pressure σ (equation 5.42).

$$\sigma = \frac{C \cdot V^2}{2 \cdot A \cdot d} \tag{5.42}$$

Steady state power consumption P can be calculated from:

$$P = \frac{V^2}{R_2} \tag{5.43}$$

In pneumatic systems equation (5.2) was used for volumetric flow rate. It appeared again as equation (5.30) for the electrodynamic model. It is again repeated, but this time in its electrostatic form as expression (5.44):

$$Q = \frac{P}{\sigma} = \frac{2 \cdot A \cdot d}{C \cdot R_2} \tag{5.44}$$

The breakdown potential of dry air is around 3000 volts/mm and about twice this for vacuum [5-23]. It is higher still for most polymer dielectric materials, so a potential difference of 3000 volts across a 1 mm thick dielectric should pose few problems. Of course, this voltage can be increased, yielding higher retention forces, in which case care must be taken to avoid air bubbles and other inhomogeneities in the gripper dielectric, imperfect dielectric to electrode contact etc. [5-22]. Notice that ε is considerably smaller than its electromagnetic counterpart μ. Consequently the available retention pressure is correspondingly reduced. However, at scales under 1 mm these rules no longer hold true (see Chapter 7 "Miniature and micro-Grippers")

To obtain a similar idea of time constant we must employ equation (5.45)

$$\tau = C \cdot R \tag{5.45}$$

where capacitance C can be calculated from expression (5.40).

However, in the model of Figure 5.64, there are two resistances R_1 and R_2. During charging C initially behaves like a short circuit hence the smaller R_1 decides the time constant in (5.45). During discharge the current path is through both resistances hence the sum of R_1 and R_2 must be used in equation (5.45). However, R_1 is usually very small compared to R_2 and so can normally be neglected.

Extensive test data has been compiled by Krape which shows that in most cases the measured value of electroadhesive force is almost always lower than that calculated [5-19]. In fact in many tests the characteristic was found to be approximately linear as opposed to the square law suggested by equations (5.41) and (5.43). This is not surprising as it is almost impossible to achieve complete contact over the entire interface area between two surfaces. Compliant or fluid backed dielectrics can be used to improve the dielectric to object surface contact [5-24, 4-17].

Example: A gripping surface with charged electrode area of 20 cm^2 has a 1 mm thick dielectric of $\varepsilon_r = 4$ and an applied voltage of 3000 volts.

where:
ε_0 $8.85 \cdot 10^{-12}$ [F/m=N/V^2]
ε_r 4.0
A $20 \cdot 10^{-4}$ [m^2]
d $1 \cdot 10^{-3}$ [m]
V 3000 [V]

Inserting these values into (5.41) gives:

$$F = \frac{8.85 \cdot 10^{-12} \cdot 4 \cdot 20 \cdot 10^{-4} \cdot 9 \cdot 10^6}{2 \cdot 10^{-6}} \approx 0.32 \text{ N}$$

and because $\sigma = F/A$ gives the retention pressure, $\sigma \approx 160$ N/m^2. Clearly, this is a much lower value than that obtainable from a comparably sized electromagnetic gripper.

To obtain a similar idea of time constant τ we must use equation (5.45) to obtain the capacitance, C.

$$C = \frac{8.85 \cdot 10^{-12} \cdot 4 \cdot 20 \cdot 10^{-2}}{0.001} = 71 \text{ pF}$$

To give roughly the same time constant as the magnetic device in a previous example, $\tau = 0.063$ seconds, we would need:

$$R = \frac{\tau}{C} = \frac{0.063}{71 \cdot 10^{-12}} = 887\,\mu\Omega$$

For this resistance, power dissipation is given by (5.43):

$$P = \frac{U^2}{R} = \frac{3^2 \cdot 10^6}{887 \cdot 10^{-6}} = 0.01 \text{ W}$$

From (5.44) this gives a power consumed to retention pressure ratio of:

$$Q = \frac{P}{\sigma} = \frac{0.01 \text{ W}}{160 \text{ N/m}^2} = 63 \cdot 10^{-6} \text{ m}^3/\text{s}$$

In actual fact a resistance of $887\,\mu\Omega$ is a little unrealistic. Something in the 10s of $M\Omega$ range is more likely given power supply internal resistance, leakage etc. [5-25]. This suggests a power consumption in the region of 100's of mW according to (5.43) yielding a force to power ratio similar to that of the electromagnetic gripper. However, equation (5.45) shows that under such circumstance the time constant will be correspondingly reduced.

Although for practical purposes the available lifting force is somewhat lower for electroadhesion than magnetoadhesion this method of prehension may be used with a wider range of object material types. All metals whether ferrous or non-ferrous can be handled.

Electrically conducting non-metallic objects such as those fabricated from carbon fibre, conducting polymers, most semiconductor materials [5-25] etc., can also be handled by electroadhesion.

5.4.2
Electroadhesive Prehension of Electrical Insulators

For electrically insulating materials electroadhesion can also be used but the basic principles of force generation are different and the forces involved cannot be so easily calculated [5-26].

There are four major types of electrical polarisation: Electronic, atomic, dipole and interfacial. For electroadhesive prehension purposes only the last two are of interest and their contribution is better described as:

- Permanent polarization due to molecular permanent dipole moment.
- Induced polarization as a result of an applied electric field.

The former is weaker and is subject to the effects of temperature, particularly in the case of liquids and gasses [5-27]. The latter, much stronger, is what is used in the electroadhesion of insulating materials.

Neither homogeneous dielectric materials nor homogeneous electric fields actually exist in nature [5-28] making precise calculation of the forces involved virtually impossible. Furthermore, any crystal structures present in the dielectric will tend to have their own, separate dipole moments, which usually dominate over those possessed by single molecules. Given that most polymers are at least partially crystalline, these unpredictable structural polarisabilities are often responsible for the overall electroadhesive effect [5-29].

From the fundamental electrostatic theory we have the basic expression (5.39). Previously, the polarisation component P_m was simply treated as a scalar. However, at the molecular level, where highly polarizable materials are concerned, this is rarely the case. Consequently, when an electroadhesor is to be used to prehend insulating materials, formula (5.41) is no longer applicable. Now we must consider what is happening at a molecular level to see why electrostatic attraction of dielectric materials can occur.

In an electrically conducting medium, such as metal, any charge which is applied will disperse through the conductor in the form of a current. In an insulator this is not possible, so a charge build up occurs on the surface. This takes the form of electrons, or holes (positive charges), being attached to the molecules from which the material is made. These electrons cannot flow from one atom to the next as in a conductor, so the only way an atom can shed its spare electrons is by turning the molecule to which it is attached until the negative end of one molecule makes contact with the positive end of another molecule thus allowing the charges to be neutralised. In a solid, the molecules are usually so rigidly bound as to make such large rotations and displacements impossible. However, as these molecules try to rotate due to the effects of these applied charges, a torque is experienced. Because the molecules are firmly attached to one another, the combination of such forces produces a net force on the surface of the object which causes it to adhere to the gripper dielectric. This effect is known as polarisation P_m and is related to the molecular structure and electric field by equation (5.46).

$$P_m = \alpha_0 \cdot E \tag{5.46}$$

α_0 molecular polarisability of dipole
E applied electric field strength [V/m]

In some cases, given long enough, the molecules ability to rotate or the electrical resistance of the material may be small enough to allow the charge to leak away. This is known as dielectric relaxation. Polarisation, P_m is exponentially proportional to the dielectric relaxation time, τ as shown in equation (5.47). As so many different kinds of polarisation (atomic, molecular, structural, interfacial etc.) can take place both simultaneously and in isolation, it is not possinle to equate polarisation accurately with dielectric constant ε_r as was done for the simpler model earlier [5-28].

$$P_m = k \cdot E \cdot e^{-t/\tau} \tag{5.47}$$

k constant (related to dielectric loss factors)
e exponential constant (2,7182)
τ dielectric relaxation time
t time

Now, current density is given by J (A/m^2):

$$J = \frac{dP_m}{dt} \qquad \text{and so current} \qquad I = A\,\frac{dP_m}{dt}$$

Power consumption $\quad P = AV\,\dfrac{dP_m}{dt} = AEd\,\dfrac{dP_m}{dt}$

Force F on a dielectric is normally expressed as a three dimensional vector quantity as the cross product of polarisation and electric field strength E, or using electrical charge as in the Faraday equation (5.48)

$$\vec{F} = \vec{q}_m \times \vec{E} \tag{5.48}$$

or in the form of prehension pressure σ

$$\vec{\sigma} = \vec{P}_m \times \vec{E} \tag{5.49}$$

whereby q is the charge through molecular polarisation. However, as we are concerned with only the retention force in the vertical direction we can reduce (5.49) to scalar form in order to find the retention pressure (5.50).

$$\sigma = \frac{F}{A} = \frac{q \cdot E}{A} \qquad [\mathrm{N/m^2}] \tag{5.50}$$

As found previously, the ratio of power consumption ($P = IV$) to retention pressure s in a dielectric of thickness d with electric field strength E is given in equation (5.51)

$$P = I \cdot E \cdot d = \frac{q \cdot E \cdot d}{t} \qquad [\mathrm{W}] \tag{5.51}$$

Using the relationship $Q = P/\sigma$ we obtain (5.52)

$$Q = \frac{dA}{t} \qquad [\mathrm{m^3/s}] \tag{5.52}$$

Most common polymers have dielectric constants which lie between 2 and 5 [5-22], but dielectric relaxation times can vary from less than a fraction of a second for polyamides and polystyrene to several thousands of seconds for the higher molecular weight substances such as high density polyethylene, PVC and PTFE [5-30].

Unlike vacuum suction and magnetoadhesion, electroadhesive forces do not permeate through the object material as deeply. Being the result of charge generation at an interface between two dissimilar dielectric materials, they tend to provide a surface-only force. This can be very useful when applying this technique to the removal of single sheets of material from a stack of the same and is used in this respect for paper handling, textile fabric destacking etc. [5-29].

Experimental results show that with fields in the region of 3 kV/mm cohesive forces for most textile fabrics, polymers and leathers lie in the region of 15 to 100 N/m^2 [5-29]. When such a gripping device is tilted at an angle of 90°, objects already prehended are retained mainly due to shear, rather than simple cohesive forces. These may be in excess of an order of magnitude greater than comparative cohesive retention forces [5-26]. For this reason, cylindrical electroadhesive devices onto which a flat, non-rigid object can be rolled are greatly superior to simple planer electroadhesive surfaces [5-25]. In addition to the peeling action of a cylindrical electroadhesive surface, such configurations can be exploited for improved object retention. The considerably greater shear forces available mean that heavier objects may be more reliably prehended than with planar gripping surfaces. Furthermore, continued rolling in excess of a full 360° rotation allows the object to be very securely held [5-26]. The table below shows the cohesive and shear retention pressures respectively for a range of object materials [4-14, 4-17].

Because the object is a dielectric, the electrical resistance can be greater than $10^9\ \Omega$. This results in a considerably smaller Q than experienced by the other astrictive techniques, but at the expense of a greatly increased time constant.

For electrically conducting objects, the acquisition and release times can be very rapid according to equation (5.45). For electrically insulating objects, the charge does not leak away so rapidly. This is not a problem for object acquisition as the gripper can be energised prior to contact. However, when power is removed, the object will not be released immediately due to residual charge and the dielectrics natural relaxation time (5.47). Fortunately this can be expedited both electrically and mechanically. The incorporation of an additional resistance in parallel with the gripper will reduce the time constant according to (5.45), though at the expense of increased power consumption resulting in a lower effi-

Material	Retention pressure σ (N/m²)	
	Cohesive pressure	Shear pressure
Aluminium Foil	200	> 1000
Unidirectional carbon fibre	60	150
Woven carbon fibre	20	40
Woven glass fibre	20	60
Woven rayon	27	100
Woven cotton	15	150
Knitted cotton	20	60
Smooth leather	93	> 1000
Polyvinyl chloride foil	40	600

ciency (5.52). Due to potential damage from electromagnetic radiation caused by electrical discharge etc., the inclusion of a small high voltage relay to short circuit the gripping surface after power removal is only appropriate in cases of relatively small, and hence low capacitance, devices. Larger capacitance devices, i.e. those with larger surface areas, must dissipate power into a resistance with the attendant increase in discharge time constant. Where appropriate, a more practical method is to assist object removal mechanically by means of plastic pegs which may be forced through small holes in the gripping surface. The problems of object removal are less pronounced when cylindrical gripping surfaces are used. In these cases, provided only part of the object surface is in contact with the gripper, the object can simply be rolled free (see Figure 10.17) [5-31].

Though much lower forces are available with electroadhesion when used with non-conducting objects, such gripping techniques are applicable to a very wide range of object materials including paper, textiles, polymers etc. Relatively light, and particularly film and sheet constructions, are especially suited to this method of handling. This includes living as well as inert structures [5-32] where the technique of electroimmobilisation can be used to temporarily, and harmlessly, secure insects for examination, photographing etc. Furthermore, both magnetoadhesion and all forms of electroadhesion are usable in vacuous environments where vacuum suction clearly is not.

Some improvements in prehension ability can be achieved through a judicious choice of gripper dielectric materials. For example, the use of compliant surfaces is beneficial, in particular fluid backed [4-17], or soft silicone rubber dielectrics [5-33]. The compliant nature of such materials helps the gripper surface to mould to the profile of the object thereby ensuring a more uniform physical contact between the dielectric and object surfaces. However, such good physical contact can exacerbate the problems of object release due to surface tension between the compliant gripper and smooth object surfaces. A phenomena which can also be used to advantage (see Chapter 7).

Despite much apparent confusion regarding the effects of humidity on electrostatic attraction, totally dry air is not the best environment for electrostatic charge generation. The forces of electroadhesion initially increase in the presence of moisture and only decrease significantly with much larger levels of humidity [5-29]. Similar observations have been made for the frictional charging of materials where a peak in the charging of most fabrics and polymers lies in the range 20% to 60% relative humidity [5-31]. Given that in the case of an electroadhesor, gripping force is maintained by means of a constant electric field, charge leakage will result in an increase in power consumption and hence higher Q rather than a reduction in retention pressure.

The following table lists a range of important parameters for each type of astrictive retention technique. These are typical figures and, except in the case of vacuum suction, are by no means maximum values. Such limiting factors are determined mainly by the object being handled rather than the prehension technique.

Astrictive gripping method	**Object material types suitable for prehension**	**Typical retention pressure [N/m²]**	**Steady state volumetric flowrate [m³/s]**	**Typical rise and fall time constants**
Vacuum	Any relatively rigid, non-porous surface	50,000	$> 10^{-4}$	10 ms, $<$ 1 s
Magnetic	Magnetically susceptible materials	100,000	$\approx 10^{-3}$	$>$ 20 ms
Electrostatic[a)]	Relatively flat, electrical conductors	200	$\approx 2 \times 10^{-3}$	1 ms, 10 ms
Electrostatic[b)]	Almost all materials provided these are flat and relatively light	50	$\approx 2 \times 10^{-3}$	100 ms, $>$ 1 s

a) Used with electrically conducting object materials.
b) Used with electrically insulating object materials.

The potential lifting forces due to vacuum suction reach a theoretical upper limit of 100 kN/m² though, as already mentioned, less than half this figure is more realistic in practice. Smoothness of the object surface is a further limiting factor making this technique almost unusable with porous materials. Though very efficient, relatively fast, inexpensive and suitable for use in situations (such as petro-chemical and inflammable gas industries) where all electrical systems must be specially constructed to intrinsically safe standards, vacuum suction cannot be used in low pressure environments. This is of growing importance in view of the semiconductor industry's increasing exploitation of total in-vacuum manufacturing.

Magnetoadhesion has the advantage of ease of use and only simple low voltage circuits are needed. The available retention pressure is very high and limited mainly by the relative permeability of the object material. Heat losses due to electrical resistance in the windings are responsible for the comparatively greater power consumption for a given mass retention. Though having a greater lifting capability than the other astrictive methods, it is limited to magnetically susceptible materials.

Though enjoying a much wider range of applications in terms of the prehension of object material types, electroadhesion is limited to the retention of relatively flat, low mass objects. Its main strength lies in areas where vacuum suction and magnetoadhesion are unsuitable; for example the ability to handle non-ferrous, porous or delicate materials.

Extending electroadhesion to use with dielectric materials by means of molecular polarisation is somewhat more problematic. Though the efficiency is extremely high due to the very low power consumption, the retention pressure is very limited and the time constant long compared to the other astrictive techniques. Its main advantage lies in the ability to handle almost any material, albeit when only in relatively light sheet or film form.

Where electroadhesive techniques really come into their own are at micro-scales where the other astrictive techniques are impractical. This is the subject of Chapter 7.

6
Contigutive Prehension

Prehension techniques which rely on direct contact – contiguity between gripper and object surfaces, are termed *contigutive*. The exact nature of the post-contact holding force can be chemical, thermal adhesion or simply reliant on surface tension forces. This latter is particularly relevant to micro-grippers which will be discussed separately in Chapter 7.

6.1
Chemoadhesion

Adhesives are used extensively for the purposes of both permanent and temporary surface bonding. In terms of robot grippers, only the latter scenario is of interest. The use of disposable chemical adhesives for the automated handling of materials, like most other techniques has a long and interesting history. A patent for a paper sheet feeding mechanism using adhesive surfaces was originally filed in 1941 [6-1], and a similar design for textile handling in 1961 [6-2]. In both cases adhesive tapes capable of being automatically wound on were the means by which these methods could be continuously used. The types of adhesive which may be used on such tapes are many and varied and further information on their chemical and physical nature can be obtained elsewhere [6-3]. For the purposes of their application to robotic prehension, it is sufficient that they provide a contigutively activated retention force and, in the case of non re-usable adhesives, can be rapidly replaced after their adhesive properties have expired. As in the example depicted in Figure 6.1, this usually entails their implementation in the form of a tape which can be wound on periodically to reveal a fresh, unused adhesive surface. However, recent advances in polymer chemistry have led to the development of adhesives which have re-usable (permanently tacky) characteristics. The requirement for such a *permatack* adhesive is that it must have enough adhesive power to be capable of several hundred operations before cleaning is required, but not so much adhesion that it becomes difficult to remove the object when release is desired. Furthermore, it must be physically robust enough to sustain several tens of thousands of pick and place operations before eventual replacement of the adhesive head is necessary. In addition, such adhesives should be made from inexpensive, non-toxic, environmentally friendly substances.

The technology of adhesives encompasses an extensive mixture of disciplines including chemistry, mechanics and materials science. This text is not intended to be a treatise on

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adhesives, but a quick look at the basic chemistry should prove useful in understanding the attributes of an adhesive which are important in terms of re-usability.

Before vulcanisation, natural rubbers often exhibit a degree of stickiness which usually increases with temperature. The addition of sulphur causes curing and an eventual loss of tacky characteristics [6-4]. Some synthetic rubbers however, cannot form cross links between their molecular chains and are therefore uncurable and consequently maintain a permanent tack. For example, when isobutylene is polymerised with isoprene it forms a copolymer – the synthetic rubber known as "butyl rubber". This has permanent tack, though like natural rubbers, it can be cured by the addition of sulphur. Polyisobutylene, on the other hand, is a homopolymer similar to polyethylene and cannot be cured [6-4]. Polyisobutylene is a clear, inexpensive, permanently tacky, viscid jelly substance which is water washable and retains most of its adhesive properties when wet. However, the solidity of polyisobutylene is proportional to, and the tack inversely proportional to, molecular weight making a trade off between physical resilience and adhesive properties difficult.

Plasticized synthetic rubbers may also be designed to have permatack properties. On its own, styrene butadiene is a block copolymer, that is to say, repeating units occurring in the polymer chain do so in blocks, i.e. several styrene molecules followed by a number of butadiene and so on in an alternating sequence [6-5]. However, if it is melted under pressure, together with about 5% aliphatic oil (liquid paraffin), the oil is soaked up and the result is a permanently tacky elastomer. A wider analysis of the various grades of styrene-butadiene rubbers and solvents appropriate to the design of specific adhesive formulations can be found elsewhere [6-6].

Plasticized polyurethane compounds have sometimes been employed in the manufacture of children's toys. These elastomers can be made permanently tacky and durable, but also exhibit considerable elasticity. When used in robot grippers, this elasticity can be a disadvantage in that it results in a relatively short retention time giving rise to problems of premature release. In such cases, once an object is prehended it must be secured by secondary means within a few seconds. Such an operation is not as superfluous as it sounds. The use of contigutive retention is most applicable to the acquisition of an uppermost layer from a stack of panels or sheets made from the same material. This is usually a very rapid operation, which once achieved leaves the object in a position to be secured mechanically.

Polyol/isocyanate mixtures can also be used to produce permatack elastomers exhibiting much longer holding times. Unfortunately, they tend to suffer the same compromise between mechanical resilience and tack exhibited by polyisobutylene [6-7]. Some vinyl based adhesives, such as "Magnatac" [6-7], have all the desired properties of permanent tack, durability and water washability. However, most loose their tack when wet and cannot sustain solvent washing. This loss of tack in the presence of moisture can be used to advantage. Whereas most of the adhesives which are still active when wet, such as the previously mentioned polymeric elastomers, require some degree of scrubbing to remove dust and lint particles, magnatak looses its tack completely thereby allowing contaminants to be removed with less effort and greater speed.

With regard to adhesive tapes, Parker and colleagues [6-8] found that the adhesive force reduces approximately linearly with use. Their own tests yielded a 50% force deterioration after about 25 cycles using the same section of tape. This of course, is also applicable to re-usable adhesives except that the adhesive surface simply requires periodic cleaning after protracted use.

As noted by Parker and colleagues, deterioration in adhesive properties, whether of tape or permatack types, takes place after the first pick, and continues with each subsequent pick and place operation. This was quantified by Hall [6-9] as shown in equation (6.1).

$$F = \alpha \cdot N^{-k} \tag{6.1}$$

α constant dependant on surface properties and contaminants
N number of fabric releases
k material dependant constant

Clearly, for a surface which does not shed dust or lint k will approach zero. Tests on textile fabric pick and place systems have shown that over 30,000 operations can be achieved before adhesive pad replacement is necessary [6-7].

Naturally, the required pressure varies somewhat between smooth and rough surface textures, though in all cases pressures in excess of 3 kN/m^2 were found to be adequate. Also, as pointed out by Parker [6-8], dwell time had an influence. With the 25 samples tested this was found to be less than 0.25 seconds, with an apparent trade-off between applied pressure and the necessary dwell time.

This concept may be quantified by taking into account the effects of exponentially decaying retention pressure σ_0 with prehension time t_0. Given an initial retention pressure σ_1 equation (6.2) shows such a mathematical relationship.

$$\sigma_0 = \sigma_i \cdot e^{-N \cdot t_0} \tag{6.2}$$

e exponential constant (2,7182)
σ_0 time dependant prehension pressure [kN/m^2]
σ_i initial contact pressure [kN/m^2]
t_0 Retention time [s]

Power will only be expended during the initial contact phase. The applied pressure σ_i is given by force F divided by area A.

$$\sigma_i = \frac{F}{A} \tag{6.3}$$

The initial prehension pressure results in a deformation d of the adhesive layer. The volume of the adhesive mass is given by the product $A \cdot d$, whose deformation leads to the power dissipation given in expression (6.4)

$$P = \frac{A \cdot d \cdot \sigma_i}{t_i} \tag{6.4}$$

Dividing this by the pressure given in equation (6.2) results, once again, in a value analogous to volumetric flow rate Q in equation (6.5)

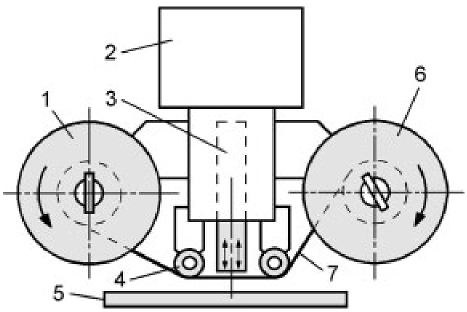
$$Q = \frac{P}{\sigma_0} = \frac{A \cdot d \cdot e^{\mathrm{N}t_0}}{t_\mathrm{i}} \tag{6.5}$$

For a perfect adhesive σ_i is zero and hence Q also zero. Clearly, Q will be smaller for a relatively hard (large Young's modulus) adhesive than for a softer one. Which is why the very soft elastomer adhesive coated rollers used for dust and fluff removal from clothes are of little use as robot grippers for textile handling! Also, as t_i increases so Q decreases and as the requirement for t_0 increases so will Q increase.

The use of adhesive tapes in paper [6-1] and textile [6-2] handling has a long history with many patents being filed along the way. Adhesive tapes have two disadvantages:

- A relatively large and expensive mechanism is required to increment the tape after each (or a small number of) cycles.
- The tape must be periodically replaced. Tape replacement requires a complete halt in the system operation and a corresponding period of temporary loss of production.

An alternative is to have the tape housed inside a cassette unit allowing either automated replacement, or at least rapid manual exchange. Unfortunately, this is more expensive and the problem of physical size and a large number of moving parts still remains. However, it is a method which has seen much interest and for which several patents have already been filed. Figure 6.1 shows the basic concept of adhesive tape feeding and application. Once positioned over the object to be prehended, a small section of tape is pressed onto the surface by means of metal shoe driven by a solenoid, pneumatic cylinder or similar actuator. To release the object the shoe is retracted and rotation of the tape take-up spool causes the adhesive tape to be parted from the object surface. At the same time the tape is incremented a little in order to provide a fresh adhesive surface for the next operation.

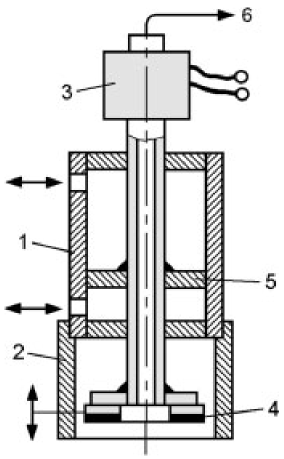


1 spring tensioned feed spool
2 pneumatic or electromagnetic actuator
3 shoe
4 tape guides
5 flat object
6 motor driven take-up spool
7 adhesive tape

Fig. 6.1: Adhesive tape gripper

Similar mechanisms to that shown in Figure 6.1 have been used by both *Pfaff* and *Durkopp* in commercially available integrated sewing systems [6-10]. In a similar vein, Jacobs and colleagues [6-11] invented a system where a continuous tape mechanism was housed in a cowl through which air suction could be applied. This provides a continuous retention force after ply separation and the initial prehension provided by the tacky surface. This combination of techniques can be useful when the adhesive in question has a limited holding time.

Figure 6.2 shows a simple permatack adhesive based contigutive gripper by which ply separation of most types of fabric may be achieved. Starting with the adhesive surface retracted, the gripper is held over the top of the stack with the surrounding cylindrical collar in contact with the top ply. The adhesive surface is then forced down onto the top ply where it adheres to the fabric. As depicted in Figure 6.3, the gripper must then be simultaneously lifted and rotated through between about 90 and 120°. This action causes even knitted fabrics to separate successfully in around 98% of cases [6-7]. Immediately after lifting, air suction is applied to the centre hole through the adhesive pad. This is not intended to assist in holding the ply but to detect multiple ply acquisition. The differential pressure sensor at the top of the gripper in Figure 6.2 distinguishes between one or multiple plies, and may be set as desired for different material air permeability and thickness in conjunction with a sensitive signal conditioning circuit [6-12]. Such devices can be obtained, with or without pneumatic sensor and circuitry as required [6-13].



1 double acting pneumatic cylinder
2 collar
3 differential pressure sensor
4 permatack adhesive
5 piston
6 slight negative pressure inlet

Fig. 6.2: Textile gripper using permatack adhesive

Figure 6.3 shows the gripper, illustrated in Figure 6.2, in operation. After acquisition of an object by a gripper having permanent long term tack, object removal must be considered. This must be achieved in a controlled manner and can be facilitated in a number of ways including the passing of non-adhesive pegs through the gripping surface to push the panel away [6-14]. Similarly, the arrangement devised by Hall [6-9] uses a gripping surface divided into squares which are allowed to pass through a mesh thus causing fabric release as the gripping surface is retracted. Alternatively, the panel may be lifted with part of the material uncovered thereby providing an edge which may be secured by mechanical means such as a clamp. The gripper may then be lifted free leaving the panel at its destination. The first two methods have the advantage of being capable of releasing the fabric without making contact with the surface below, however clogging of the holes or mesh is more likely with highly flocculent fabric than with the latter method.

With regard to the design shown in Figures 6.2 and 6.3, the object may be ejected at its destination by simply allowing the gripper to descend so that the collar secures the fabric against a surface (table top etc.). The adhesive pad is then retracted thus mechanically re-

Fig. 6.3: Gripper being used for ply separation. (Photo: courtesy Brynmoor-Jones Library, University of Hull)

leasing the fabric panel. In the event of multiple acquisitions, the plies may simply be rejected in a similar manner at a different location.

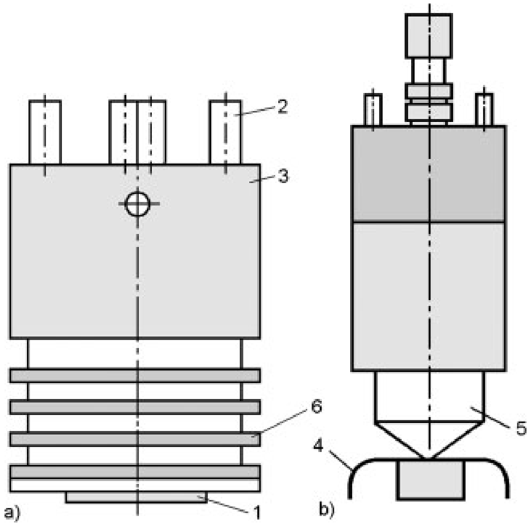
In addition to ply separation and reusability, permatack adhesives can be used to make surface selective gripping heads. That is to say, they can be designed so as to be pressure sensitive to only compliant materials, such as textiles, and not to hard surfaces, such as tables tops. Often the fabric panel must be orientated using vibratory feed tables [6-15]. These are highly polished and are consequently very good candidates for chemical adhesion. Direct contact with such surfaces should be avoided as it is extremely difficult to remove the gripping head afterwards often resulting in some of the adhesive being left behind. This not only contaminates the feed table, but also reduces the effectiveness of the gripper. However, by situating the permatack adhesive at the bottom of a slightly concave recess in the gripping head, this problem can be avoided and the gripper becomes sensitive only to materials with a degree of flexibility and flocculence.

In some circumstances, localised prehension is inadequate, particularly in the ply separation and lifting of large panels of fabric which are required to be laid flat and undistorted. For these tasks, as discussed previously, a roller mechanism is the usual solution regardless of the means of adhesion employed. Conner filed a US patent [6-16] for a system consisting of a roller having a hole in the surface through which the tacky side of a tape protruded. This gives only a localised grip on the fabric, the roller action providing a degree of ply separation. As with most tape methods, a rather elaborate mechanism is required to feed the tape, from the loading spool, along the length of the roller. Again, the use of permatack adhesives obviates the need for a large plurality of moving parts as the adhesive elastomers may be formed into or applied to the surface of a cylinder.

6.2 Thermoadhesion

Small droplets of water suspended between the surfaces of a gripping head and object may be frozen by the sudden application of a small quantity of liquid carbon dioxide or nitrogen. The ice which is formed works as an adhesive layer (ice bridge). Moreover, it prevents direct contact with the gripper. At a temperature of about – 10 °C, a temporary bond between the two surfaces is formed. Increasing the temperature of the gripping surface then melts the ice causing the object to be released. An original patent for a device using this technique for textile handling was filed by *Sutz* [6-17], and some similar systems have become commercially available more recently [6-18]. Fortunately, most textile fabrics and many polymer and composite materials are not damaged by sudden, rather large, temperature gradients [6-19]. Problems can arise with certain materials such as ceramics or materials which are coated with thermally activated adhesives. The retention force is amazingly large when compared to similarly sized vacuum suction heads (about 1 N/mm^2 or 50 to 100 times larger).

Just as in the case of chemical adhesives, retention time is related to dwell time through various constants particular to the adhesive and material to be handled. Consequently it is possible, through the corresponding thermodynamic properties, to find a similar relationship for thermal gripping heads. Figure 6.4 shows two design examples.



1 Peltier module
2 media and control line connector
3 housing
4 workpiece
5 cold contact element
6 cooling ribs

Fig. 6.4: Two examples of thermal contigutive grippers
a) surface gripper (*NAISS*)
b) point gripper (*AFT*)

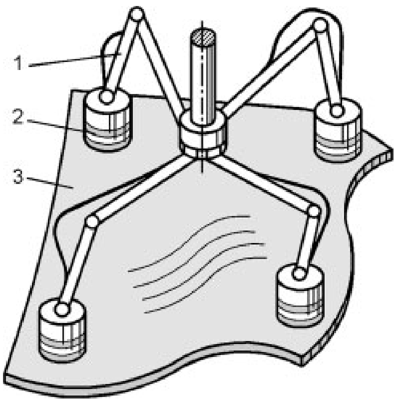
The freezing of small amounts of water is completed in less than a second. Heating elements or warm spray can be used for release and the detachment process is also shorter than a second. The quantity of warm water spray needed amounts to little more than about 0.1 ml per gripping cycle. For small objects, such as microcomponents, a *Peltier* module may be used as the cooling element. These are somewhat slower but have the advantage of heating and cooling in one element. After prehension, reversal of the electrical current causes heating of the gripper surface thus facilitating object release. However, *Peltier* modules operate far too slowly for the handling of larger objects. Figure 6.5 shows a comparison of different gripping principles and their respective properties.

The handling a large textile panels demands a multiplicity of thermal gripping heads. One such example is shown in Figure 6.6. Melting the ice with warm compressed air has the added advantage of an additional pneumatic rejection force. For a gripping head diameter of 50 mm a retention force of about 70 N can be expected. Experience shows that drying of the gripping point is fairly rapid [6-20].

	intrussive prehension	ingressive prehension	impactive prehension	astrictive prehension	contigutive (chemical) prehension	contigutive (thermal) prehension
gripper reliability	◐	◐	○	◐	○	●
damage free grip	○	○	○	●	●	●
retention force	◐	◐	○	◐	○	●
material flexibility	◐	◐	◐	○	◐	◐
workpiece flexibility	◐	◐	◐	○	○	●
grip velocity	●	◐	●	◐	◐	◐
environmental dependence	●	●	●	◐	○	◐

Fig. 6.5: Comparison of several prehension principles with respect to their suitability with textile objects: full circle = very suitable, open circle = unsuitable

The cross-linking capability of the textile material and the roughness of the contact surface of the *Peltier* module play an important role here. There exists a three phase boundary line while the interface tensions between the separate phases (liquid-gas; gas-solid; solid-liquid states) are in equilibrium.



1 stiff but adjustable arm
2 thermal gripper
3 large textile panel

Fig. 6.6: Thermoadhesive gripping system with several gripping heads

According to [6-21] the thermal adhesive prehension force F_{ad} can be obtained from the following equation:

$$F_{ad} = \frac{W_{sl}^{ad} \cdot A_r}{\delta} = \frac{\sigma_{lg}\,(1 + \cos\Theta) \cdot A_r}{R_Z} \quad [\mathrm{N}] \tag{6.6}$$

σ_{sl}, σ_{lg}, σ_{gs}	interface stress [N/m^2]
δ	layer thickness [m]
Θ	contact angle at the triple point (vapour, liquid, solid state)
W_{sl}^{ad}	adhesion work [J/m^2]
A_r	resulting effective area [m^2]
R_Z	average depth of roughness [m]; surface finish

Retention pressure is then:

$$\sigma_{ad} = \frac{F_{ad}}{A_r} = \frac{\sigma_{lg}\,(1 + \cos\Theta)}{R_Z} \tag{6.7}$$

The relationship is derived from the *Young equation* for the interface stress which is illustrated and explained in Figure 6.7.

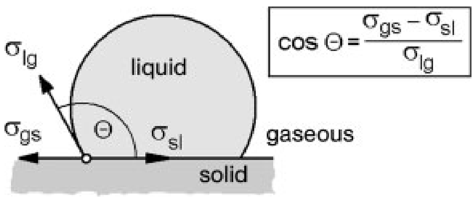


Fig. 6.7: Explanation of the *Young equation*

The deployed thermal energy e is given for thermal gripper heads by (6.8):

$$e = m \cdot s \cdot \Delta T \tag{6.8}$$

m	mass of the water droplet [kg]
s	specific heat of water (4184 kJ/kgK)
ΔT	temperature change until freeing of the water [K]

The power P is obtained from the following equation:

$$P = \frac{m \cdot s \cdot \Delta T}{t_r} + P_V \quad [\mathrm{W}] \tag{6.9}$$

t_r	time required for freezing of the water [s]
P_V	power loss [W]

The power loss P_V depends on the freezing method. For example, in the case of a *Peltier* element by $I^2 \cdot R$. Thus the freezing of 1 mg of water within 1s for a temperature change of 50 °C requires (neglecting some effects as the crystallization, radiation of energy etc.) a power of 0.215 W.

As in (5.2) for pneumatic, (5.30) for electromagnetic and (5.44) for electrostatic Q is the ratio between power P given in (6.7) and prehension pressure σ_{ad}

$$Q = \frac{P}{\sigma_{ad}} \tag{6.10}$$

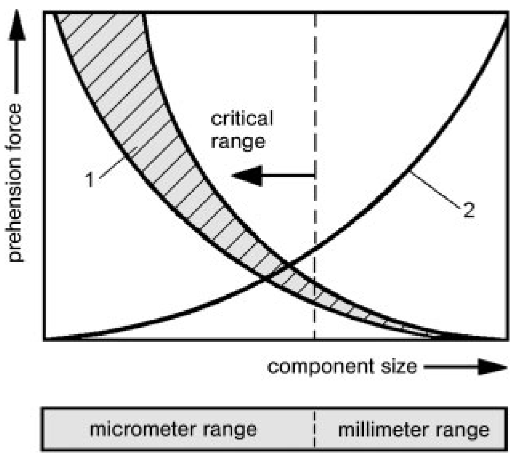
The thermal conductivity of air at 300 K is 2.68 W/mK [6-22]. This is one order of magnitude greater than that of most textile fabric materials. For this reason, the melting time of the water droplet is determined basically by the gripper head and the thermal conductivity of air.

Although cooling realized by liquid nitrogen or liquid carbon dioxide is very rapid and the basic consumables are relatively inexpensive, storage and supply has additional costs. For this reason electric Peltier modules have become widely established.

7
Miniature Grippers and Microgrippers

The world has seen a dramatic reduction in the size of components used in the manufacture of almost all modern equipment. Miniaturisation started around the end of world war two with the subminiature thermionic valve. The transistor, by virtue of its solid-state construction, led to a substantial reduction in size which was augmented by a significant reduction in power supply volume – both battery and mains powered. Printed circuit technology, later enhanced by integrated circuits, and eventually their surface mount counterparts, led to the microcircuits in common use today. Now micro and nanotechnolgy lead the way in further miniaturisation. However, micro-component manufacturing techniques differ considerably from those used at larger scales which in turn have a considerable impact on automation leading to the need for micro-robotics.

Unfortunately it is not always possible to simply scale things down on a linear basis when going from the handling of objects many centimetres wide to the prehension of micro-components barely visible without the aid of a magnifying glass or even a microscope. In fact, many effects which are hardly detectable at macro scales can lead to severe problems with tiny, low mass components. On the other hand, gripping techniques which are impractical with large components often present themselves as the only viable solution to handling problems at submillimeter level.



1 disturbing forces
2 necessary prehension force

Fig. 7.1: Relationship between prehension force and size for micro-components

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In cases of astrictive prehension, the cubic scaling down of a parallelepiped volume (and hence mass) results in a quadratic reduction in prehension surface area (and hence prehension force). Consequently, weaker astrictive forces such as electroadhesion become more relevant as object size reduces (Fig. 7.1). The disadvantage lies in the effects of disturbances such as unwanted electrostatic (intermolecular and atomic) attraction, ferromagnetic, surface tension, adhesion due to contaminants etc. (Fig. 7.1). The same holds true for forces due to acceleration [7-1].

7.1 Impactive Microgrippers

Virtually all gripper manufacturers have expanded their product lines to include miniature grippers. Most of these devices are designed following standard techniques used at larger scales. This can lead to serious problems at micro scales since mechanical gears cannot be arbitrarily downsized. Scaled down joints and levers can then withstand only very weak forces [7-2].

7.1.1 Electromechanically Driven Impactive Microgrippers

Figure 7.2 shows a miniaturized jaw gripper with external dimensions 25×32 mm. Despite its reduced size, the gripping jaws are ball-guided. They are driven by a pneumatically stimulated slotted-plate. The weak friction of the ball-guiding allows relatively long fingers to be employed. The position of the fingers can be determined by a sensor, making this gripper suitable for precision tasks. The bottom jaw must be augmented with appropriate gripping fingers.

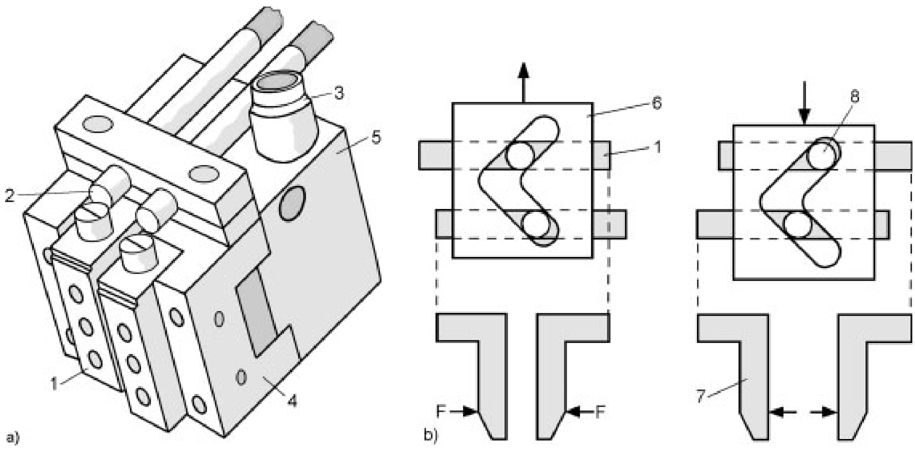
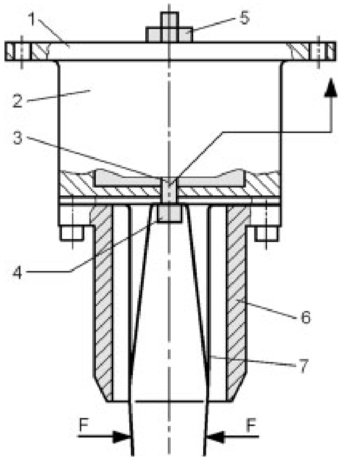


Fig. 7.2: High precision miniature gripper with double action (*Montech*)
a) projectional view, b) actuation principle
1 ball-guided bottom jaw, 2 touch sensor, 3 air supply, 4 base plate, 5 pneumatic actuation,
6 slotted-plate, 7 gripping finger, 8 reel, *F* gripping force



1 connection flange
2 actuation
3 pull rod
4 fastening screw
5 stroke adjustment
6 protective casing
7 flat spring finger

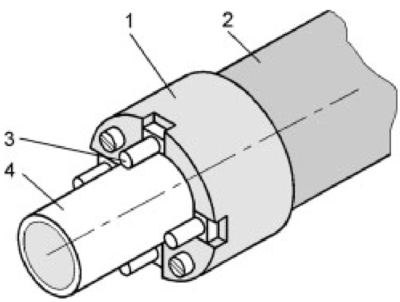
F gripping force

Fig. 7.3: Principle of a miniature three-finger gripper with simple kinematics (*SCHUNK*)

The three-finger gripper displayed in Figure 7.3 operates with tweezer-like fingers. The gripping fingers resemble two-layer leaf springs allowed to slide toward one another. Depending on the gripper model, the actuation can be achieved pneumatically or electromagnetically so that small and sensitive components can be gripped at high repetition rates. The finger travel limit is continuously adjustable.

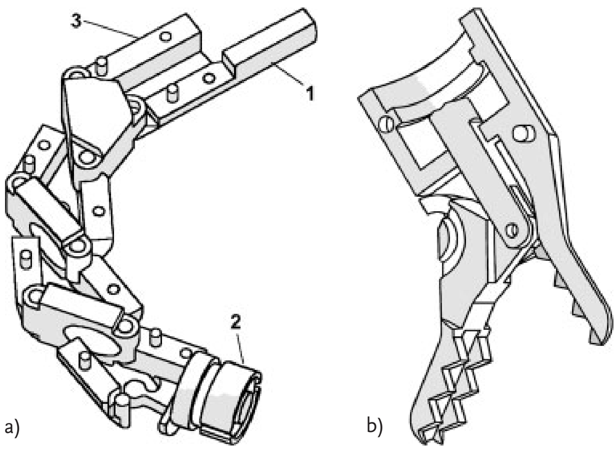
Electrically operated grippers are slightly slower in comparison to their pneumatic equivalents but possess the important advantage that they do not require compressed air lines. A miniature gripper having gripping rods which can be used both for internal and external prehension is shown in Figure 7.4. Instead of 4 prehension elements one can configure it as a two-jaw parallel gripper. In comparison to the overall size, the 10 mm travel range for the entire opening is relatively large. The gripper is mounted by means of four M2 screws and the gripping force and finger speed can be adjusted by a potentiometer.

Miniaturized robot (or telemanipulator) arms with multilink structures are often required for positioning. Size reduction of the manipulator is not always easy owing to constructional problems. Figure 7.5 shows a joint arm and the corresponding angular gripper. The arm is formed according to the principle of successive switching of four-element gears. If, in addition, the arm is pivotal at the base phalanx, then the end-effector is able to cover a large area.



1 housing
2 motor
3 gripping pin
4 workpiece

Fig. 7.4: Miniature electrical gripper with a diameter of 30 mm driven from a 24 V DC motor (*phd*)



1 actuator coupling
2 mounting flange
3 mounting base

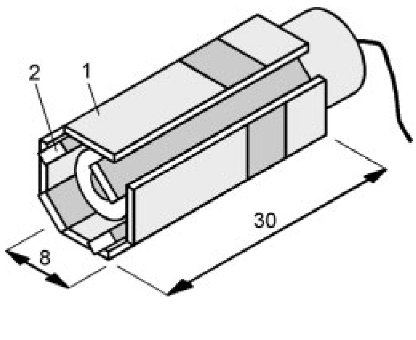
Fig. 7.5: Prototype of a miniaturized joint arm (ZIS Industrietechnik)
a) joint arm
b) gripper

The joint arm depicted in Figure 7.5 has a diameter of 9.2 mm and is only 42 mm long when fully outstretched. The angular gripper is of the same diameter and has a length of 8 mm. The unusual swivel joint design (moving jaws, arm links) not only resembles biological archetypes but in fact based on the interlocking spherical shells of a crab arm and a scissor grip. The joints and gripper are actuated by wire cords passing through the interior of the manipulator allowing the employment of larger prime movers as would be required when fully integrated.

7.1.2
Thermally Driven Impactive Microgrippers

Where more force is required, but speed is not of paramount importance, thermal techniques may be used. One such approach relies on the bending of a heated bimetallic strip for actuation. The principle is based on the thermal expansion coefficient mismatch between two different materials, for example aluminium ($23.0 \cdot 10^6$/K) and silicon ($2.6 \cdot 10^6$/K).

A design by *Greitmann* and *Buser* [7-3] utilises 1.5 mm long gripper fingers fabricated using etching and metallic deposition techniques. Each pair consists of an actuator finger and a resistive force sensor finger with a sensitivity of about 600 Ω/N as shown in Figure 7.6.



1 bimetallic finger
2 spring steel gripper jaws

Fig. 7.6: Thermally actuated microgripper
Dimensions in mm

Though small, the deflection of the tip of the fingers is proportional to the heating power which means that the gripper stroke can be easily adjusted by varying the electrical input power. With the dimensions given above the theoretical deflection of the finger tip is about 750 nm/K. For a tip deflection of 200 microns the finger temperature can be estimated to be about 300 degrees Celsius. Due to the low thermal mass of the actuator and the good thermal conductivity of silicon, the gripper can be opened and closed at a frequency of about 15 Hz [7-3].

So called *Shape Memory Alloys* (SMA), such as NiTi, and shape memory polymers have the unique property of quickly reverting to a pre-determined shape on heating. Such properties can be exploited in the manufacture of small impactive gripping devices [7-4]. Though greater forces can be achieved than with electrostatic or piezoelectric devices, operation is relatively slow and lifetimes are limited to between 30,000 and one million open and close cycles making its potential for industrial applications somewhat limited. For medical applications this presents few problems as such tools would be considered to be disposable and the construction of such a device using many of the other techniques so far discussed would be prohibitively expensive.

The following table compares relevant characteristics for actuator devices used in the design of impactive robot grippers.

Actuator	Energy density [J/cm^3]	Max. strain [%]	Max. pressure [N/mm^2]	Response time [s]	Supply
Pneumatic	0.2	–	0.8 (at 8 Bar)	10^{-1}	Compressed air
Piezoelectric	$4.8 \cdot 10^{-4}$	0.2	30	10^{-3}	Voltage
Shape memory	10.4	3	150	0.1 to 1	Current

Minigrippers in the form of pincers are required in minimally invasion surgery. The atraumatic grippers are designed for applications in laparoscopy (an endoscope for the examination of the abdominal cavity) and keyhole surgery. All external edges of such grippers, and especially those of the gripping jaws, are rounded, smoothed and polished to avoid damage to tissue. This type of pincer can be also manufactured as a single mechanical part as shown in the example presented in Figure 7.7. The gripper consists of a NiTi wire which is only 0.63 mm thick. The opening and closing of the fingers of the pincer takes place thermally. The gripper possesses a corrugated jaw structure which ensures better gripping and prehension of tissue samples during the intervention. The jaw shape is realized by microstructuring of the wire.

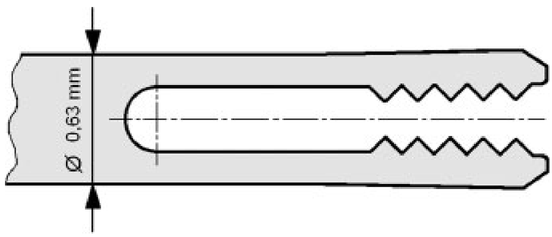


Fig. 7.7: Minipincer for surgical applications based on nickel-titanium (shape memory alloy)

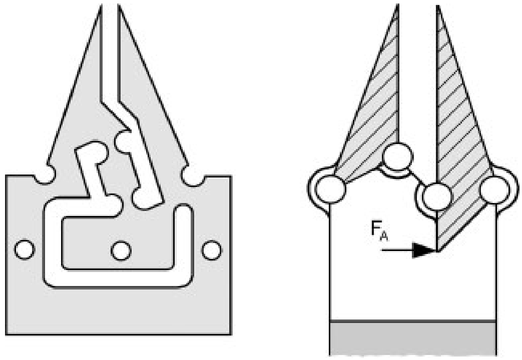
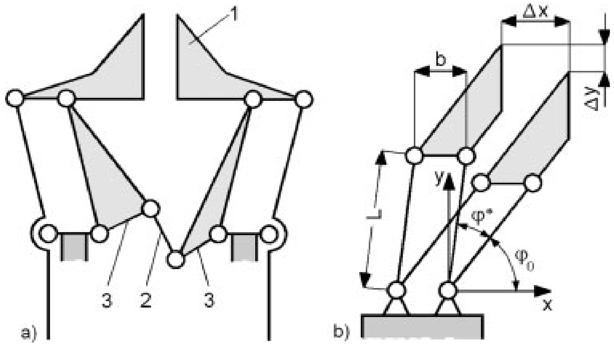


Fig. 7.8: Centring gripper with solid joints and the corresponding kinematic model
F_A actuation force

Instead of conventional gear systems, miniaturization permits the exploitation of materials elastic properties. The gripper shown in Figure 7.8 is designed with bending springs allowing it to be manufactured from a single substrate [7-5]. It is based on a gear mechanism with four joints operating in opposing directions. The two jaws always perform contrary motion and hence centre the object in the gripper.

The gripper gear shown in Figure 7.9 can be extended into a parallel jaw gripper. This is illustrated in Figure 7.9 a.



1 gripper jaw
2 coupler
3 crank

Fig. 7.9: Miniature parallel-jaw gripper gear
a) parallel gripper
b) gripper jaw offset

Calculation of the prehension kinematics should be carried out in such a way that the offset of the working point Δy caused by the circular translation remains as small as possible (Fig. 7.9 b). The relationship between the travel of the gripper jaws Δx and the offset Δy is given by the following expressions [7-6]:

$$\Delta x = |L \cdot \cos\varphi_0 - L \cdot \cos(\varphi_0 + \varphi^*)| \tag{7.1}$$

$$\Delta y = |L \cdot \sin\varphi_0 - L \cdot \sin(\varphi_0 + \varphi^*)| \tag{7.2}$$

where:

L length of the gripping finger
φ_0 angle of the finger relative to the x-axis

Assuming a small angle ϕ^*, transforming expressions 7.1 and 7.2 gives:

$$\Delta y = \frac{\Delta x}{\tan \varphi_0} \tag{7.3}$$

The offset Δy is minimized when the angle ϕ_0 is equal to 90° and the length L of the gripper arms is obtained from

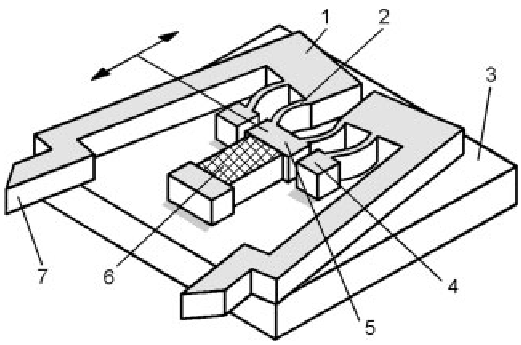
$$L_{\min} = \frac{\Delta x}{\varphi^*_{\max} \cdot \sin \varphi_0} \tag{7.4}$$

The separation b has no effect on the kinematic properties.

The presented structures are referred to as *Compliant Mechanisms*. The joints are designated as material or solid body joints. The following points should be taken into account when designing such joints:

- The number of joints should be as small as possible.
- The joints, and hence the entire gripper, develop a restoring force.
- The instantaneous centre of rotation for solid body joints moves with increasing rotation angle.
- In order to obtain useful prehension strokes the joints should allow for a pivoting angle of at least 10°.
- The joints must be capable of sustaining a persistent folding without fatigue. Injection moulded guidance joints made from polypropylene achieve more than 1 Million cycles.
- Not all known gripper kinematics can be realized as a solid body joint; shear joints are especially difficult to represent in this way.

Actuation of the gripper can be realized, e.g. with linear actuators made from shape memory alloys. They enable travel as large as 5 % of the actor length and prehension pressures of up to 150 N/mm^2 (tensile stress) in continuous operation. The adjustment travels which are achieved in the piezoelectric fork amount to only 0.3 % of the fork length. The joint structure for the gripper depicted in Figure 7.10 is machined from a silicon wafer with a thickness of 240 µm. The fingers are connected through elastic microjoints with a

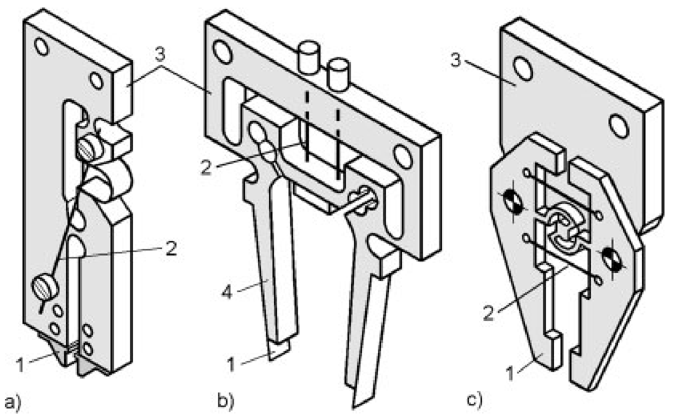


1 gripper finger
2 elastic joint
3 substrate
4 secured pivot point
5 coupling link
6 piezoelectric translator
7 gripping surface

Fig. 7.10: Silicon gripper with piezoelectric drive (*TU Ilmenau*)

piezoelectric translator. The angle levers increase their length with changes of several micrometers by a factor of 10 to 50. There are many possibilities for adjustment of the gripper jaw shape to fit the object in question.

Figure 7.11 shows examples of grippers having small external dimensions, intended for the mounting of miniature and microassemblies in a cleanroom environment. Actuation is realized electrothermally through a NiTi SMA wire [7-7]. The longitudinal strain variation amounts to approximately 3%. The tractive force leads to closure of the gripper jaws with a rather small stroke of maximum 1 mm for the device shown in Figure 7.11 c. The gripper jaws can be adapted to the workpiece size and shape.



1 gripper jaw
2 0.1 mm diameter SMA-wire
3 carrier
4 finger

Fig. 7.11: Gripper with an SMA drive
a) pick & place gripper, mass: 5 g (*University Dresden*), b) microgripper (*University Budapest*), c) double action drive

In order to improve the dynamic performance of miniaturized grippers using shape memory drives, the employment of a differential actuator is possible [7-8]. In this case two NiTi-actuators with equal adjustment forces operate against each other as demonstrated schematically in Figure 7.12 (only one gripper finger shown).

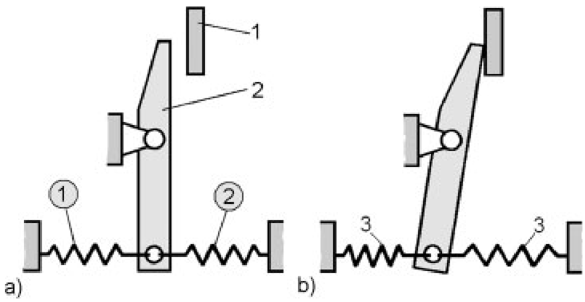


Fig. 7.12: Operation principle of a differential actuator system
a) gripper open, b) gripper closed
1 object, 2 gripper finger, 3 shape memory drive

The gripping cycle can be described as follows:
- Gripper open; both actuators (1) and (2) are cold.
- Actuator (1) heated; gripper closed. The closure time is a function of the electrical heating current.
- Actuator (1) and (2) heated = gripper open; the opening time depends only on the thermal risetime of the actuator (2) and is independent of the cooling rate of the actuator (1).
- Cooling down of both actuators before commencing a new gripping cycle.

A differential actuator with a diameter of 0.1 mm exhibits a cooling time of approximately 1 second. The shape memory drive is not suitable for continuous operation with short cycle times. Metal fatigue eventually results in failure of the SMA over prolonged use.

Flexible manipulators, controlled in a similar manner to the hexapod, have been the subject of much research (Fig. 7.13). Three shear motions are transmitted from external actuators while joints made from SMA are effective at the ends. The core region of the structure remains free for the insertion of instruments, optical fibres, etc.

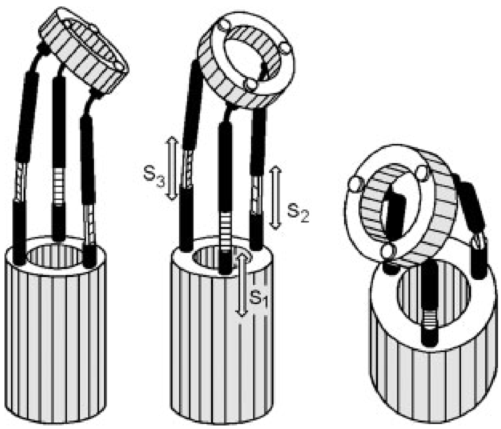


Fig. 7.13: Miniaturized gripping head (after *Müglitz*)
S shear motions

7.1.3
Electrostatically Driven Impactive Microgrippers

Expression (7.5) show the energy density for an electrostatic system.

$$W_e = \frac{1}{2}\varepsilon_0 E^2 \tag{7.5}$$

The electrical breakdown field strength in dry air is around 3000 V/mm yielding a maximum energy density of about 40 J/m^3 according to (7.5).
The energy density for the electrodynamic counterpart is given by expression (7.6).

$$W_m = \frac{1}{2}\mu_0 H^2 = \frac{B^2}{2\mu_0} \tag{7.6}$$

In an air gap a maximum magnetic field strength of about 1.5 Tesla is achievable before magnetic saturation resulting in an energy density of around 1,000,000 J/m^3. Which is why electrical motors are almost exclusively electromagnetic and very rarely electrostatic.

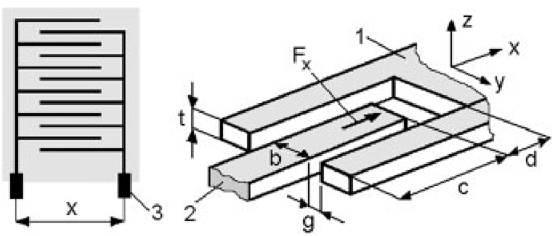
However, the breakdown field strength of 3000 V/mm is valid only for dimensions down to about 1 mm. Under a millimeter the maximum field strength approximately follows the rule in (7.7):

$$E_{\max} \approx 3000 + \frac{500}{g} \qquad [\mathrm{V/mm}] \tag{7.7}$$

where g is the gap width in mm.

Clearly, as dimensions are reduced toward the micrometre range the energy density of an electrostatic system will at some point exceed that of its electrodynamic counterpart. Add to this the constructional problems associated with winding coils at micro-scales and it is little wonder why very few electromagnetic micro-grippers exist. For this reason electrostatic actuators are predominantly used in micro-grippers.

One of the first such designs, based on the principle of the electrostatic voltmeter, consisted of two interleaved, but electrically isolated, metal comb structures to which the gripper fingers are attached as shown in Figure 7.14. When a potential is applied between the comb-shaped electrodes an electrostatic attraction force is produced forcing the combs, and hence the gripper fingers, together so instigating prehension. Disconnection of the supply and short-circuiting to remove residual charge expedites object release.



1 substrate
2 finger element
3 gripper jaws

t electrode thickness
x gripper stroke

Fig. 7.14: Electrostatic comb actuator

From the simple capacitance formulae (7.8), the equation for force can be seen again, but this time the energy equation must be differentiated with respect to the longitudinal distance x. The total force is then obtained by multiplying by the number of electrodes n giving expression (7.10).

In Figure 7.14, t is the electrode thickness and ε the permittivity (normally that of free space ε_0). The electrostatic force must also work against the spring coefficient F_x of the material from which the actuator is built together with any influences the elasticity of the gripper jaws and object may have. The inter-electrode forces perpendicular to the actuation direction are much higher than those in the x-direction. This, together with physical rigidity constraints limits the possible stroke to a few micrometers. Though gripping forces for devices of micrometer dimensions are in the nano-Newton range, the very small area of the jaws means that retention pressures of several thousand Newton per square meter are attainable.

With an effective cross sectional area $A_1 = b \cdot t$ the capacitance C_x can be calculated

$$C_\chi = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot b \cdot t}{d} \tag{7.8}$$

From the energy e stored in the capacitance C_x

$$e = \frac{C_\chi}{2} \cdot V^2 = F_\chi \cdot d \tag{7.9}$$

the resulting force F_x can be calculated

$$F_\chi = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot b \cdot t \cdot V^2}{2 \cdot d^2} \tag{7.10}$$

Given a plurality n of electrode pairs, as illustrated in Figure 7.14 (left), then the resulting force will be n times that of F_x. Movement in the x-direction is against a spring return force $F_s = k \cdot x$, whereby k is the spring constant (elasticity) of the material. Equilibrium (ceasation of gripper finger movement) is achieved when $F_x = F_s$.

$$\chi = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot b \cdot t \cdot V^2}{2 \cdot k \cdot d^2} \tag{7.11}$$

From the effective longitudinal cross sectional area $A_2 = c \cdot t$, the capacitance C_y can be calculated

$$C_y = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot c \cdot t}{d} \tag{7.12}$$

The stored energy e in the capacitance C_y

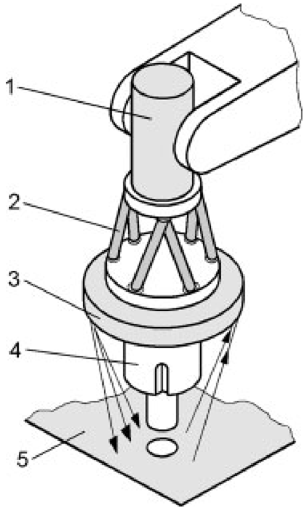
$$e = \frac{C_y}{2} \cdot V^2 = F_y \cdot g \tag{7.13}$$

gives the resulting force in the y-direction F_y

$$F_y = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot c \cdot t \cdot V^2}{2 \cdot g^2} \tag{7.14}$$

The capacitance C_y, is equal at both sides. This means the resulting F_y forces at each side of the fingers are equal in magnitude but opposite in direction thus balancing each other. This leaves only the force F_x in the x-direction as the prime mover force. Despite this, the resulting force in the x-direction is inevitably a vector sum of F_x and F_y. As the actuator-reaches the end of its stroke, differentiation of expression (7.10) with respect to d reveals a strong non-linearity as the condition $d \leq g$ approaches. Care must be taken to limit the travel of the finger to prevent contact between the two set of electrodes at this juncture.

Micro-assembly requires installation accuracies of between 0.1 and 20 μm which is much higher than in watch manufacturing. This cannot be achieved with a standard industrial robot which is why special assembly equipment is needed. The motion cycles can be broken down into coarse and fine steps, these tasks being assigned to different functional elements. Figure 7.15 illustrates the concept of a 6D-hexapod actuator with piezoelectric stacktranslators which, in conjunction with a laser triangulation system, accurately guides the endeffector to the mounting position. The six actuators can perform fine translations and rotations along and about three axes.



1 wrist axis
2 piezoelectric stack translator
3 flange with integrated laser triangulation system
4 gripper
5 mounting base

Fig. 7.15: Concept of a 6-dimensional micropositioning device (*iwb* München)

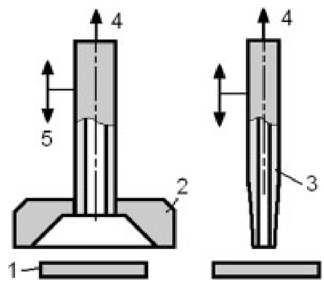
7.2
Astrictive Microgrippers

The principles of astriction, previously discussed in Chapter 5, are particularly relevant to microgrippers as they rarely include moving parts.

7.2.1
Vacuum Microgrippers

Since the advent of SMD (surface mount device) technology, miniature vacuum grippers of the form shown in Figure 7.16 have seen widespread use in the electronics sector. Vacuum prehension is relatively fast and strong enough to remove SMD components from adhesive tapes or bands. Most modern SMD assembly relies on hard automation, where position accuracy of 50 μm is adequate, rather than slower, precision robotics.

Micro vacuum grippers consist of glass or metal capillaries which can be applied to polished tips with diameters of around 10 μm.



1 SMD component
2 receiving head (tungsten carbide) with self-centring effect
3 vacuum pipette
4 vacuum
5 approaching motion

Fig. 7.16: Vacuum gripper for SMD components

The requirements for vacuum grippers applicable to micromechanical component handling are formulated in [7-9] as follows:

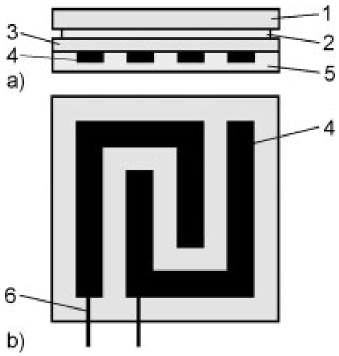
- The object must be observable during the assembly process in order to enable reaction to deviations from specified tolerances (assembling with optical position feedback).
- Prehension should take place with the lowest possible pressure and largest possible air intake diameter. The force required to hold silicon plates with an edge length of 1 mm and a thickness of 0.25 mm amounts to about 5 μN.
- The component should be prehended preferably at its centre of gravity or at least symmetrically with respect to that point.

The integration of optical microsensors at the suction point is also possible. Examples include small CCD cameras and laser triangulation systems.

7.2.2 Electroadhesive Microgrippers

At even smaller scales, electroadhesion becomes highly applicable and this very simple astrictive technique can also benefit from the addition of piezoelectric actuator elements. As discussed in Chapter 5, electroadhesion is a prehension technique usable with most lightweight sheet materials, both electrically conductive and non-conductive, such as metal foil, polymer sheet, textile fabrics and many similar fibrous materials [5-25]. Furthermore, recent research has shown that electroadhesion is ideally suited to the handling of very delicate optical and electro-optical microcomponents, where other gripping techniques would damage high quality optically coated surfaces. The use of soft silicon rubber dielectrics eliminates any danger of damage to highly sensitive optical components such as micro lenses with diameters in the tens or hundreds of mm ranges [7-10]. The basic design of an electroadhesive microgripper is shown in Figure 7.17.

As with all microgrippers, object ejection can be a problem. Van der Waals forces, unwanted adhesion through surface tension, contaminants etc. all serve to hinder the release process. This problem can be solved by the addition of small piezoelectric actuators behind the electroadhesive surface [7-10]. Small vibrations can then be initiated to eject the object downwards in a controlled manner. This technique cannot be so simply implemented with impactive grippers as the ejection trajectory from a single, two or even three point contact tends to be unpredictable.



1 piezoelectric actuator
2 acoustic coupling
3 electroadhesive substrate
4 electrodes
5 dielectric
6 high voltage connections

Fig. 7.17: Electroadhesive microgripper
a) side view
b) underside view

The nature of the acoustic coupling between the piezoelectric actuator and the gripper substrate can be critical in ensuring controlled release. An acoustic resonator with too little damping can have the effect of releasing the object immediately after it has been acquired. Too much damping and release cannot be achieved as and when desired.

7.3
Contigutive Microgrippers

The moistening of the fingers as an aid to prehension and separation of sheets of paper is done without thought during our normal daily lives. The surface tension forces responsible for this effect tend to become even more apparent at microscales thus obviating the need for chemical or thermal adhesion. When used as an interface between two planar solid surfaces, a liquid droplet can provide a considerable binding force. As discussed in Chapter 6, many non-curing adhesives effectively act as high viscosity liquids to provide a temporary bond between two surfaces. However, at micro scales even low viscosity liquids can be used for contigutive prehension. This has some significant advantages in that light solvents, such as ethanol which can be made to evaporate rapidly, can be used.

A single droplet of fluid will attempt to adhere to all surfaces it is in contact with. When sandwiched between two planar solid surfaces, above and below, a capillary column will be formed as the surfaces as moved away from one another as shown in Figure 7.18. This results in a rotationally symmetrical fluid bridge between the two surfaces. The effects of surface tension on the constant volume fluid column constantly try to cause a reduction in the column radius R_1. This results in a force between the two planar surfaces [7-11].

Should the droplet meniscus bow inwards as a result of the contact angle then a prehension force between gripper and object will be produced. Object release may be achieved either mechanically or by thermally evaporating the fluid. Figure 7.19 shows the steps in a prehension and release process [7-12].

The higher the viscosity of the fluid, the higher the retention force. Unfortunately, viscosity tends to limit evaporation for rapid release solvents like ethanol. Analysis reveals that prehension is achieved through a combination of capillary and cohesive forces [7-13].

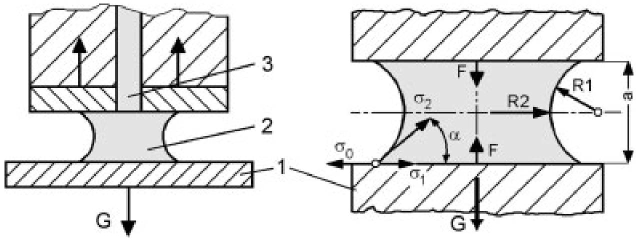


Fig. 7.18: Principle of the capillary gripper (gripper and fluid bridge)
1 object, 2 fluid, 3 dispersion hole, *R*1 radius of the meniscus, *R*2 radius of the droplet, *a* gap, α contact angle, *F* force due to droplet surface tension, *G* gravitational force, σ_0 capillary pressure (air to solid substrate), σ_2 pressure due to droplet surface tension

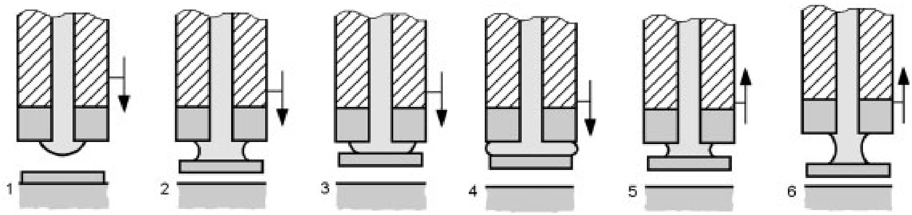


Fig. 7.19: Contigutive prehension process using fluid droplet

Following the analysis given by the original researcher in this field [7-14], the general equations of force are given by a combination of capillary and cohesion forces (7.15)

$$F = p_K \cdot \pi \cdot \alpha^2 \cdot \psi_0^2 + 2 \cdot \pi \cdot \gamma \cdot \alpha \cdot \psi_0 \tag{7.15}$$

where γ is the surface tension (N/m) and p_K is the capillary pressure (N/m^2) as defined by *Bark* [7-15] in expression (7.16).

α	gap width [m]
γ	surface tension [N/m]
p_K	capillary pressure [N/m^2]
$\alpha \cdot \psi_0$	radius of the fluid bridge [m]

Equation 7.16 gives the capillary pressure p_K according to [7-12]

$$p_K \cdot \gamma \cdot \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{7.16}$$

ψ_0 is a dimensionless quantity expressed as the ratio between the radius of the neck of the fluid column at its thinnest point R_2 and the distance between the two surfaces. Substituting this and expression (7.16) into equation (7.15) gives the more usable formula (7.17)

$$F = \pi \cdot R_2 \cdot \gamma \cdot \left(\frac{R_2}{R_1} + 3\right) \tag{7.17}$$

Normally R_2 will be larger than R_1 making the prehension force several times larger than the product of R_2 and the surface tension γ (which is typically around 0.226 N/m for ethanol [7-12] and similar solvents). This will give values for gripping force in the region of tens of mN for fluid column parameters of millimetre and submillimetre dimensions, which is in line with experimental results [7-13].

Whether such a prehension method will be usable in practice will depend heavily on the application. The use of solvents is not always welcome in modern industry and other, more environmentally friendly, liquids such as water would, in the majority of cases, be too slow to evaporate in order to facilitate object ejection.

In the animal world "dry" adhesive systems are common. Examples include lizards, spiders etc. Based on the original work (commonly cited as JKR) which deals with spherical point contacts, expression (7.18) gives the removal force needed to part such a dry contact [7-16].

$$F_c = \frac{3}{2}\pi \cdot R \cdot \gamma \tag{7.18}$$

whereby:
R is the contact radius [m]
γ is the specific surface energy [J/m^2]

However, more recent investigations suggest that these are not limited to spherical point contacts but include a variety of shapes including toroidal surfaces. Consequently, expression (7.18) must be slightly modified to fit more realistic situations [7-16].

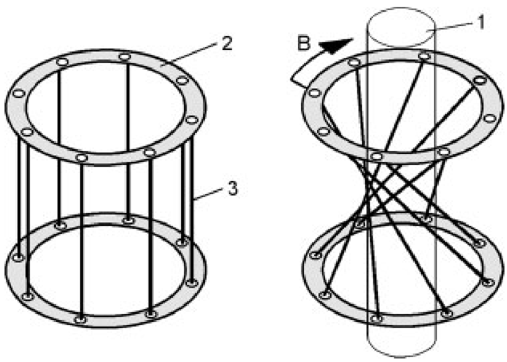
8
Special Designs

This Chapter deals with some rather special designs intended for specific tasks. In many cases the examples shown are hybrids utilising two or more of the standard prehension techniques already dealt with in former Chapters. The interested reader may also like to consult Chapter 14 where a number of case studies are considered.

8.1
Clasping (Embracing) Grippers

Certain forms of impactive gripper are also capable of wholly or partially enclosing the workpiece.
- Closed embracing: the object held is inserted into the gripper.
- Partial embracing: the workpieces are elongated and need not be inserted into the gripper.

Figure 8.1 shows such a gripper comprising two rings which are coupled by elastic cords. The prehension force is developed by a constriction of the cords resulting from rotation of the two rings in opposing directions. The gripper diameter can range from 15 to 200 mm.
Due to its delicate handling nature this form of gripper has found usage with the prehension of a variety of different shaped objects and is not limited to solid forms. Long



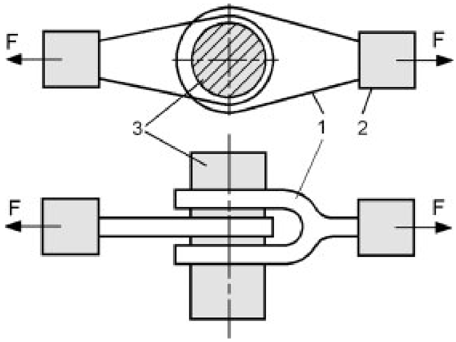
1 workpiece
2 rotatable ring
3 elastic cords

B closing motion

Fig. 8.1: Principle of operation of the elastic cord gripper (*Knight*)

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

ISBN: 978-3-527-40619-7



1 tension bands
2 gripper jaws
3 workpiece

F prehension force

Fig. 8.2: Prehension of an object with the help of elastic tension bands

necked bottles, open plastic sacks, glass tubes and ampoules, and also workpieces with polished or coated surfaces are just a few examples. One limitation lies in the closed design of the gripper making insertion of the object within the gripper necessary.

In addition to rotary motion in order to generate prehension forces, another configuration employing the same principle is possible using linear motion. This principle is illustrated in Figure 8.2 using two elastic ring bands held between the jaws of a conventional two finger linear impactive gripper.

Depending on elastic inhomogeneities, the object is roughly aligned with the gripper centrum. The elastic tension bands can be made from synthetic elastomer material or spring steel. The robotics company *KUKA InnoTec* has developed similar prehension concepts for the handling of luggage in which bands are used to secure the object to the grasping organs.

Compliant embracing of an object may be achieved by mechanisms similar to an elephant's trunk or the tentacles of an octopus. Each of the finger links gently holds the object with the same retention force. The basic design for a mechanical equivalent is shown in Figure 8.3. The separate finger links are driven by steel cords (prehension cord 1, release cord 2) over pulleys. When the first finger link has made contact with the object the following link will continue moving towards the object. The gripper is opened by pulling the release cord whilst the prehension cord is unwound. Many variations for the arrangement of the cords and rollers exist [8-1].

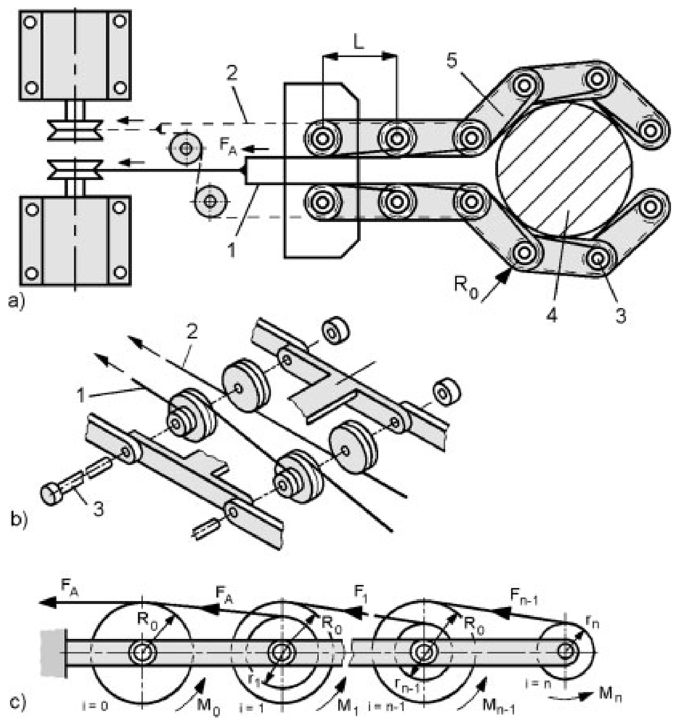
If double pulleys with different radii are used, the pulleys with radii r_i and R_{i-1} are connected by a shaft (Fig. 8.3 c).

Assuming $R_i = R_0$ it is possible to calculate the radii

$$r_i = \frac{(n-i)^2 + n - i)}{(n-(i-1))^2 + (n-(i-1))} \cdot R_0 \qquad i = 1 \ldots n \tag{8.1}$$

for any choice of R_0. The following equation for the values of the gripping moments M_i ($i = 0$ to n: number of the joint) is approximately valid under the assumption of constant length of the links ($L = \text{const}$):

$$M_i = \frac{qL^2}{2}[(n-i)^2 + (n-i)] \tag{8.2}$$



1 prehension cord
2 release cord
3 axis
4 workpiece
5 grasping organ

F_A driving force
L link length
R_0 larger pulley diameter
M moment
i transmission ratio

Fig. 8.3: Scheme of a compliant gripper with two five-link fingers [8-2]
a) schematic diagram, b) design principle, c) arrangement of the cords and pulleys.

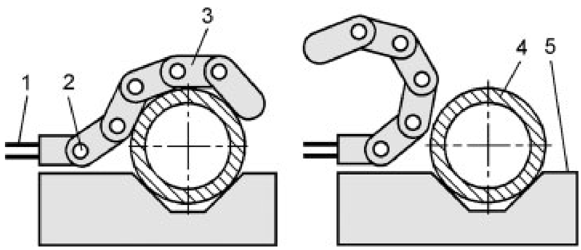
The gripping force generated by the compliant gripper is distributed uniformly along the entire gripping length. If friction effects are ignored this force corresponds to the static uniform load q:

$$q = \frac{2 \cdot F_A \cdot R_0}{L^2 \cdot (n^2 + n)} \tag{8.3}$$

Example: Determine the uniformly distributed gripping force (stiffness) q for the following values of the relevant parameters: Radius $R_0 = 10$ mm, link length $L = 30$ mm, number of links $= 10$, and driving force $F_A = 100$ N.

$$q = \frac{2 \cdot 100 \cdot 10}{30^2\,(10^2 + 10)} = \underline{0.02\ \text{N/mm}}$$

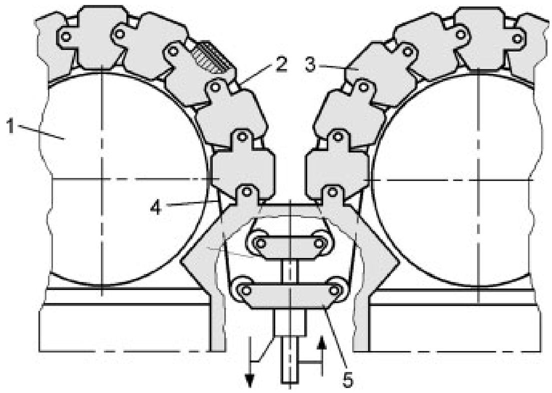
The compliant gripper can also be used in conjunction with a fixed finger or supporting prism. One possible application of such a single compliant finger is illustrated in Figure 8.4.



1 steel cord
2 joint
3 finger link
4 workpiece
5 prismatic jaw

Fig. 8.4: Single compliant finger

Figure 8.5 shows one further possible configuration employing one tension and one release cord [8-3]. The grasping organs consist of relatively short chain pieces, through which the cords pass.



1 object
2 release cord
3 finger link
4 drive cord
5 drive and release mechanisms

Fig. 8.5: Clasping gripper with cord actuated elements (1984)

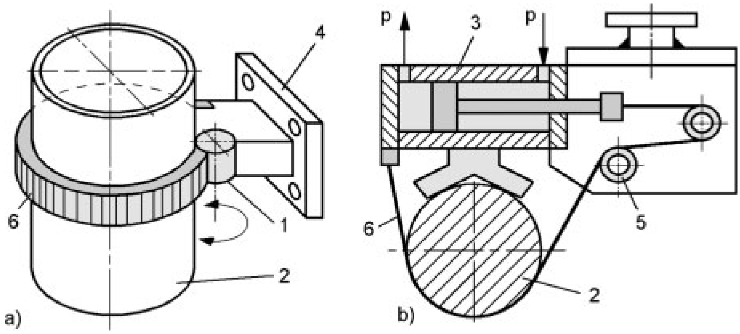
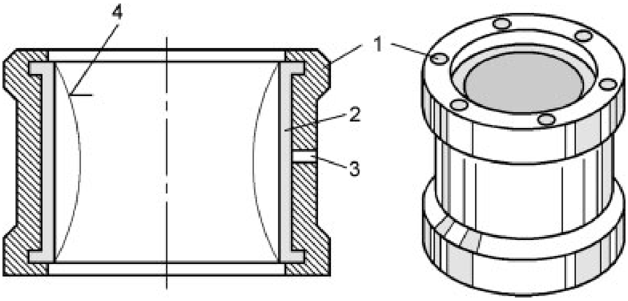


Fig. 8.6: Clasping gripper with flexible bands and object under retention
a) e.g. using a toothed belt, b) using a composite belt
1 motor, 2 object, 3 pneumatic cylinder, 4 flange, 5 guide roller, 6 belt or band
p compressed air



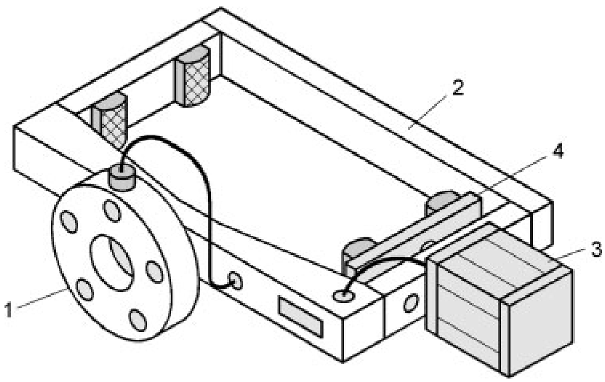
1 housing
2 rubber membrane
3 compressed air
4 arched membrane

Fig. 8.7: Rubber membrane gripper (*Sommer-automatic*)

The clasping organs of the design modifications shown in Figure 8.6 are formed into a tensioning belt (or chain). The holding force is produced either by winding or pulling the band. In both cases the upper surface of the object under prehension is well protected against damage.

Prehension can also be realized using a compliant mechanism as in the case of the tube gripper shown in Figure 8.7. The design of this gripper is rather simple. A rubber membrane expands from inside the gripper clamping the part to be held. The membrane adjusts itself to the shape of the workpiece. As with the examples shown in Figure 8.1 and Figure 8.2, insertion of the object into the gripper interior must be possible.

Similar handling strategies are also used for cast objects from which residual sand must be removed. A framed construction employing four compliant pads is shown in Figure 8.8. The position of the pads may be adjusted to the dimensions of the object.



1 flange
2 frame
3 pneumatic cylinder
4 moving plate

Fig. 8.8: Frame gripper for handling castings (*IPR*)

8.2 Anthropomorphic Grippers

As a rule, anthropomorphic grippers possess more than two grasping organs and their structure resembles that of the human hand. The fingers may be stiff or flexible and their numbers vary from 3 to 6. Fully anthropomorphic hands with many multi-link jointed fingers are of great technical interest but of little industrial relevance.

8.2.1
Jointed Finger Grippers

The grasping and manipulation potential of the jointed finger hand is determined to a great extent by its kinematic structure. The optimum number of joints is considered to be three for each finger. This corresponds to the presentation in Figure 8.9 c.

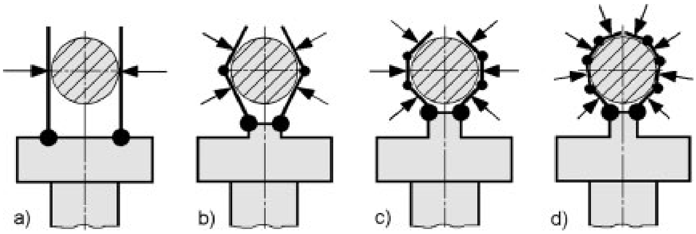


Fig. 8.9: Multi-joint two finger gripper
a) simple angle gripper, b) finger with 2 joints, c) finger with three links, d) four finger joints

The grasping proceeds in several steps, as illustrated in Figure 8.10 for a finger with three joints [8-4]. Many more gripping possibilities are available with the employment of more fingers and/or joints. The example shows prehension through shape-mating of the object which also allows a reduction in gripping force in comparison to force-matched prehension. This is also illustrated in Figure 8.19 by a typical hand configuration.

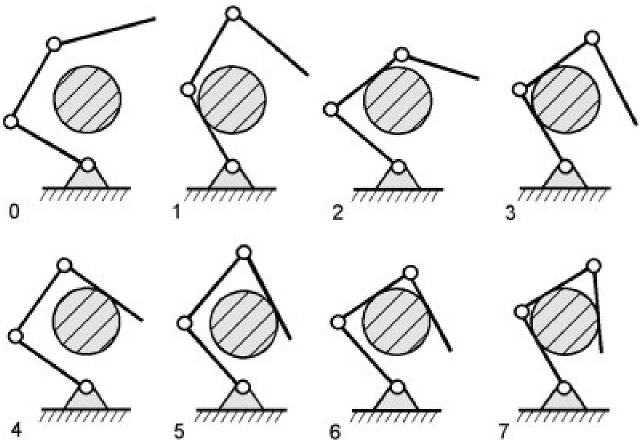
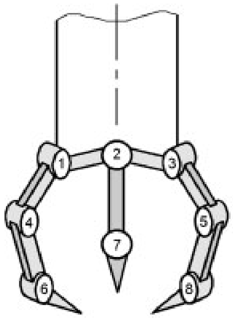


Fig. 8.10: Eight stages of prehension of a cylindrical object by a jointed finger.

The driving elements are more complicated for multi-jointed fingers because they have to be activated beyond a single degree of freedom. Most conventional prime movers are too large to be mounted within the finger joints. The drives and their interconnections must be realized in such a way that it is impossible for any part of the mechanism to reach a "dead point" thus blocking other joint movements. Consequently, for jointed finger grippers it is essential to simplify the design as much as possible. The three-finger hand (in-



joint No.	movement type	comments
1, 3		finger joint and thumb
4, 2, 5		freely programmable
6, 7, 8		positively controlled joints

Fig. 8.11: Joint scheme of a three-finger hand intended for assembly work [8-5]

tended for assembly work) depicted in Figure 8.11 is simplified and not all of the joints are freely programmable.

In each case the foremost joint is not independent of, but is positively controlled by the next joint. This helps to avoid a stiff finger contour and proportionally bend the tip as far as possible when gripping round objects. Two fingers arranged on the same side can be rotated about their basic phalanx so that it is possible to prehend with the finger tips. In the same way it is also possible to perform a clasping grip.

Multi-link finger grippers are designed primarily as three and five finger grippers, although the three-finger gripper can be controlled more easily. Figure 8.12 shows a 25 years old design from Japan.

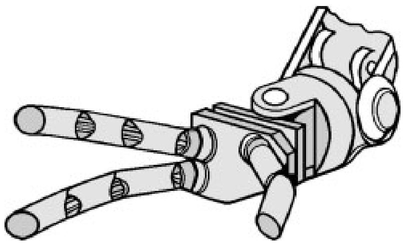


Fig. 8.12: Three-finger jointed gripper as a flexible laboratory hand with $F = 11$ [8-6]

Another example of finger mechanics is shown in Figure 8.13. When the end link of the moving finger strokes across the table surface the joint chain is displaced in such a way that motion towards the object continues. Prehension of the object occurs in the last phase. This jointed finger can be referred to as multifunctional or adaptive.

Figure 8.14 shows a multi-finger gripping mechanism (University of Bologna, 1985) which allows the prehension of randomly shaped objects with many fingers. The prototype was equipped with 20 fingers and the achievable holding torque reached 0.54 Nm [8-7].

The application fields for multi-jointed finger grippers are limited by the relatively small gripping forces allowed by the construction of the finger link connections. Swivel joints are the most commonly used junction elements for individual links.

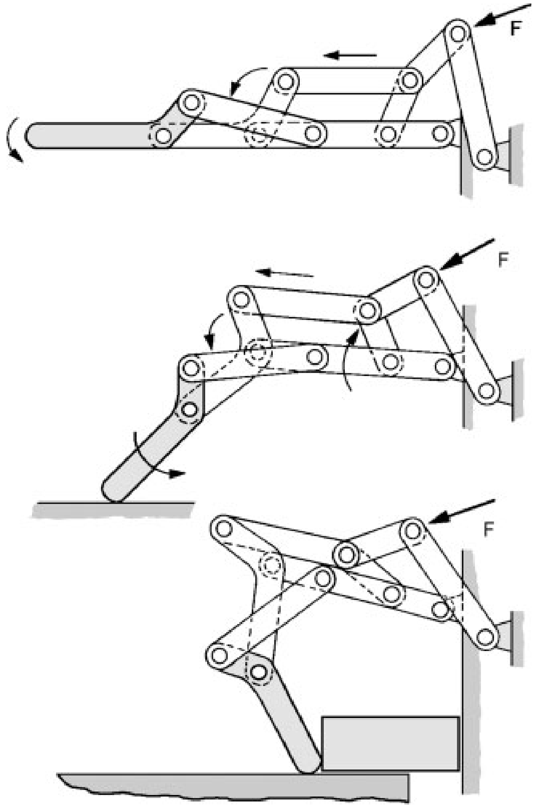
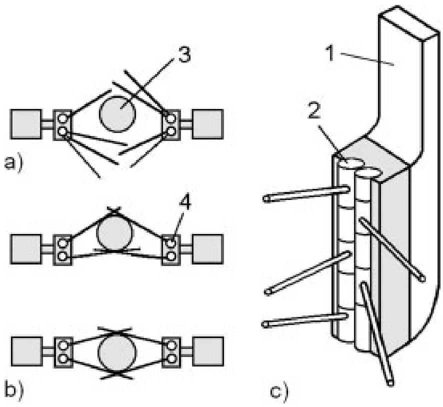


Fig. 8.13: Gripper finger (Mechanical Arm after *Ido*)
F driving force

However, it is not always necessary to control each finger link separately. Some grippers, intended for the prehension of varying shaped objects bend their links uniformly and independently of one another as already demonstrated in Figure 8.11.

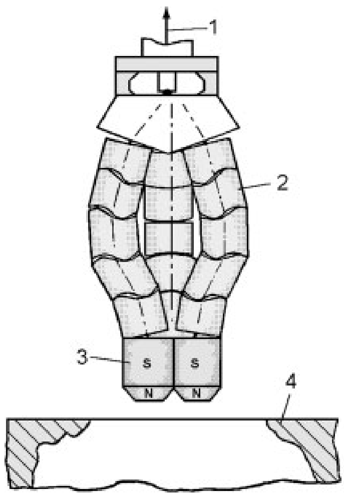
Such solutions will be considered in the following: Using the gripper shown in Figure 8.15 it is possible to grasp parts having randomly shaped inner contours. When a tensile force is applied to the steel cord, the shape of the segmented finger elements results in a spreading of the fingers. The small permanent magnets attached to the finger tips ensure that the fingers are symmetrically closed in the initial state. This hand is relatively simple and independent control of individual fingers is not possible. This means that the destination position can only be very roughly defined.

For prehension through contour matching it is advantageous to use fingers with elements capable of enclosing the workpiece. One such solution is shown in Figure 8.16, where spatially orientated parts, e.g. disordered objects lying on some surface, can be handled. The gripper consists of a fixed finger and a segmented finger which is driven from a hydraulic cylinder or similar proportional prime mover. A double sided L-shaped lever is attached to the gripper substrate. The second finger link is actuated as the piston rod of the cylinder moves outwards. At the same time the L-lever rotates about the first



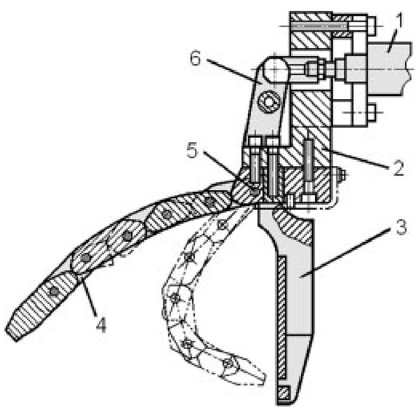
1 carrier
2 moving finger
3 workpiece
4 finger joint

Fig. 8.14: Multi-finger gripper (MIP 2 Gripper)
a) initial stage of the gripping process
b) gripped part
c) grasping organ



1 steel cord
2 finger elements
3 permanent magnets
4 prehended object

Fig. 8.15: Spread finger gripper with pull rope actuation

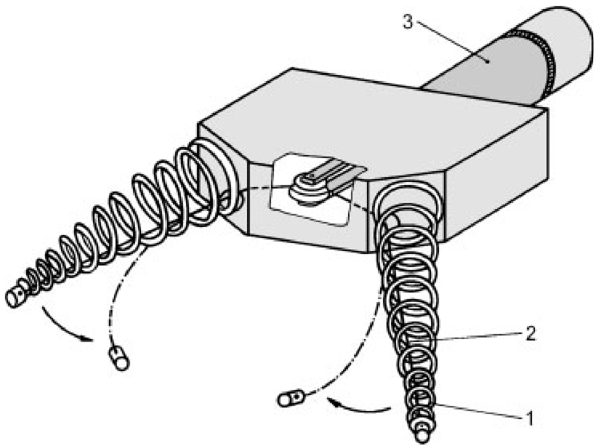


1 hydraulic cylinder
2 substrate
3 fixed finger
4 segmented finger
5 axis
6 lever

Fig. 8.16: Jointed finger gripper (French Patent B 25 J 15/02, 2354861)

joint axis. The finger links have toothed ends and transmit motion from one link to the other. This leads to bending of the segmented finger towards the fixed finger.

Many experimental grippers possess steel cords in conjunction with flexible fingers to achieve prehension by shape enclosure. Figure 8.17 shows a rather simple version of such a flexible finger. The fingers are designed as conical wire helix springs which are forced to bend by partial withdrawal of an internal steel cord resulting in object enclosure. The object is released by allowing the steel cord to return to its normal state against the spring force of the fingers. The gripping forces achievable with such mechanisms are rather small.



1 spring helix
2 steel cord
3 prime mover

Fig. 8.17: Conical fingers formed from spring wire helix

The hand depicted in Figure 8.18 is also equipped with steel cords. In contrast to the other designs it possesses a spring loaded palm which allows, in combination with the fingers, a reliably prehension of objects having different geometrical shapes. In addition to the three conventional links, each finger possesses a fourth link at its base. A pre-stressed spring and a mechanical stop are mounted at each finger joint. The springs define the relative motion of the links and bring the fingers back to their rest position. Each finger link is actuated by a cord which controls both the finger link position and the pressure whilst the finger is in motion.

Figure 8.18 a shows a finger approaching an object and Figure 8.18 b shows the changed post prehension configuration. Figure 8.18 c shows only two fingers but in practice three fingers are symmetrically arranged around the palm. The object, positioned between the fingers, is detected by an optical sensor which activates the prime mover (stepping motors). The cords are pulled so that the fingers make contact with the workpiece forcing it against the palm. When the tension of the spring, indicated by the position sensor on the palm, exceeds a given threshold the motors are stopped. This special hand is capable of handling a range of different shaped objects with prehension forces up to 100 N.

There exist many ideas for hands with jointed fingers which can be moved within the basic configuration. The basic principle of the 3-finger Barret Hand, shown in Figure 8.19 is one such example, developed further and utilized in a modular multi-finger gripper as

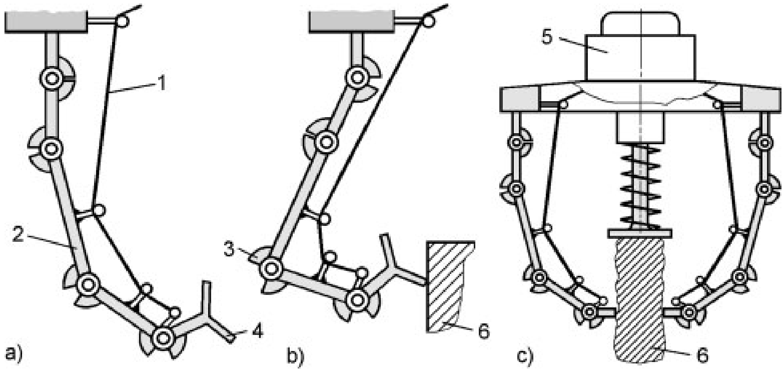


Fig. 8.18: Mechanical hand with flexible palm [8-8]
a) approaching the object, b) contact with the object, c) prehension
1 steel cord, 2 finger link, 3 joint, 4 gripper jaw, 5 motor, 6 gripped object

early as 1988 (*W.T. Townsend,* Barret Technology, Inc.). Both gripping force and gripping speed are adjustable. A separate finger can develop a gripping force of maximum 5 N.

In 1999 NASA developed an anthropomorphic five-finger hand for space missions, the so called Robonaut Hand. By the control of 14 joints it possesses 22 degrees of freedom. The materials and components used can sustain extreme temperature variations and satisfy cleanroom requirements (no gas or particle emission).

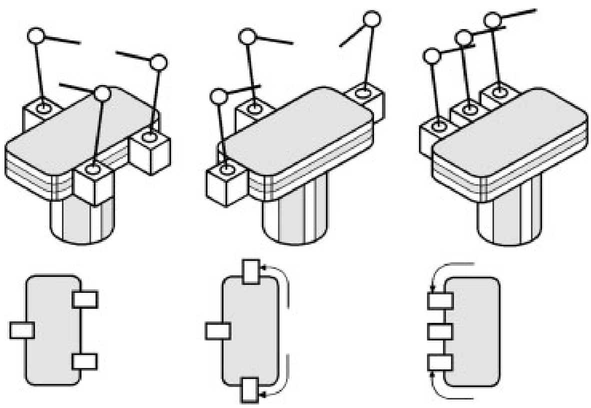


Fig. 8.19: The Barret Hand with three fingers and its configurations

In addition to holding the object against the base plate or palm, other grippers with jointed fingers prehend the object solely between the fingers (Fig. 8.20). In this case one has to distinguish between contour matching in which the fingers huddle against the object and force mating in which the object is retained solely by frictional forces.

The modern industrial sector is dominated by simple impactive grippers. Their two states, OPEN and CLOSED, are easily obtained through binary actuators (pneumatic cylinders) without recourse to more expensive proportional control. Furthermore, the two

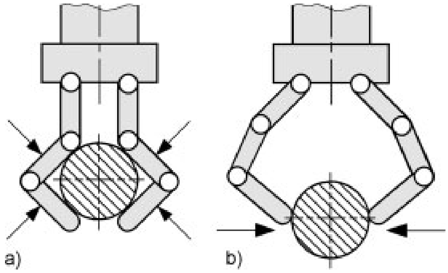


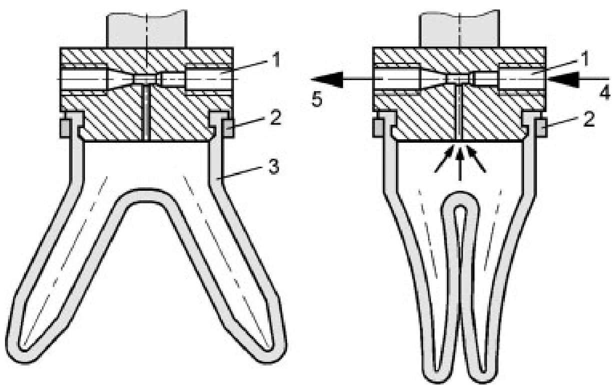
Fig. 8.20: Holding configurations with a jointed finger gripper
a) contour matching
b) force mating

states are easily defined and programmed. In contrast, the precise proportional control demanded by multi-link finger grippers require more expensive actuators and somewhat more complicated control algorithms utilising sensory feedback.

8.2.2
Jointless Finger Grippers

The grippers fingers described in the following have no mechanical joints. Their structure is based on special materials, i.e. they possess flexible material joints. This considerably reduces the number of components and consequently the price. However, the load-carrying capacity of such grippers is not very high as can be seen from the examples described below (Fig 8.21) which are designed for the handling of delicate and randomly shaped workpieces. The pre-stressed rubber fingers are spread outward in the quiescent state. The spread fingers are forced to close as air is removed (vacuum generated by the Venturi ejectors). The impactive prehension force is relatively small amounting to roughly 8 N for closed fingers.

The industrial importance of this gripper is marginal because the gripping accuracy (reproducibility of the order of $\pm$ 0.1 mm) is limited by the softness of the material and the movability of the grasping organs. However, such a prehension method has the advantage of protecting the workpiece surface.



1 venturi ejector
2 spring sealing ring
3 double finger made from neoprene
4 compressed air connection (minimum working pressure: 2 bar, maximum working pressure: 8 bar)
5 air exit

Fig. 8.21: Spread finger gripper (*Sommer*-Automatic)

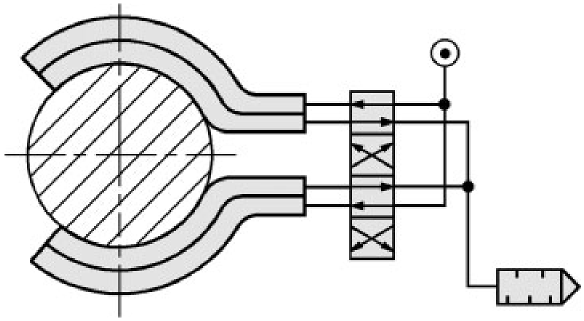
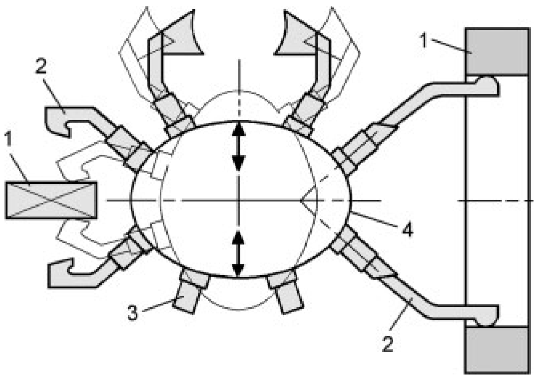


Fig. 8.22: Principle of a gripper based on multiple chamber tubular fingers [8-9]

This feature also holds for the gripper shown in Figure 8.22 which demonstrates the principle of a tube finger gripper whose fingers are segmented into chambers. The finger is bent by varying the pressure in neighbouring parallel chambers. This gripper is applicable only to the handling of relatively light parts and working lifetimes may be reduced when used with rough and abrasive objects.

In order to produce larger prehension forces the gripper fingers can be fixed to a steel ring which is deformed through hydraulic force in such a way that the attached fingers perform a gripping motion along a curved path. The principle of operation can be seen in Figure 8.23. The physical gripping range can be defined by adjustment of the grasping organs. Despite the rather simple gripper structure, this principle is actually rarely applied because of the need for precise proportional actuation.

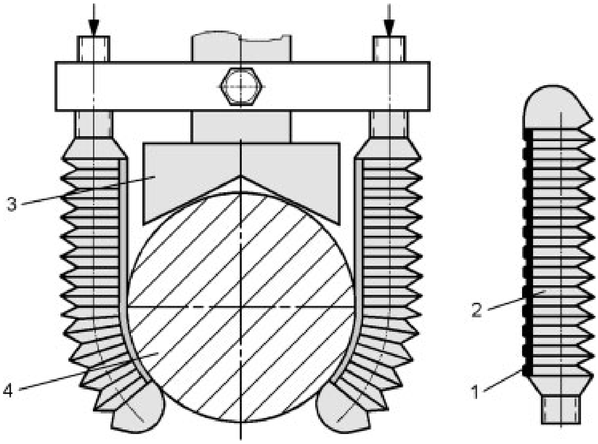


1 workpiece
2 gripper finger
3 finger holder
4 elastically deformable ring

Fig. 8.23: Principle of a gripper with material joint structure

Elastic fingers like those depicted in Figure 8.24 can match themselves to the workpiece depending on their capability to bend on the application of pneumatic pressure. The finger gripping surfaces are equipped with a flexible metal band having no elasticity along its own major axis. The finger motion is produced by this band and the folded structure when air pressure is applied. On removal of air pressure the flexible metal band acts as a return spring returning the finger to its original position.

As can easily be calculated, the achievable gripping force is dependant on the tension developed as a result of finger bend.



1 flexible metal band
2 rubber folded piece
3 prism support
4 workpiece

Fig. 8.24: Pneumatic bending finger (*Sommer*-Automatic)
Left: gripper surrounding object
Right: relaxed finger

Example: Determine the tension τ developed by the elastomer finger depicted in Fig. 8.25 and the force F developed over its surface area.

The following parameters are given: $R = 1$ cm, $L = 3$ cm, $p = 3$ bar (300 kN/m^2)

$$\text{Tension, } T = \frac{2 \cdot \pi \cdot p \cdot R^3}{L^2 \cdot (n^2 + n)} \tag{8.4}$$

Substituting the above values into (8.4) one obtains

$$T = \frac{2 \cdot \pi \cdot 300\,\text{kN/m}^2 \cdot 10^{-6}\,\text{m}^3 \cdot 1000\ \text{N/kN}}{0.03^2\,\text{m}^2 \cdot (12^2 + 12)} = 13.42\ \text{N/m}$$

the surface area, $\alpha = 72$ cm^2 (12 $\times$ 3 cm by 2 cm) and the resulting force $F = 1863$ N

The stiffness or tension τ is the average force produced per meter with which the finger can bend itself. Equation (3.53) implies a gripping force which is proportional to the pneumatic pressure. However, the elasticity (effectively spring return force) of the material has been neglected. Consequently the figure of force F calculated is a maximum and in reality it will be considerably weaker. Figure 8.26 presents a comparison of the forces when vertical and horizontal prehension is realized.

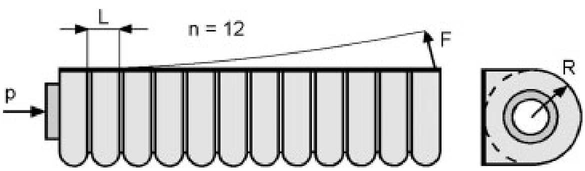


Fig. 8.25: Elastomer finger
n number of finger elements (folds), *L* width of the finger elements, *R* finger radius

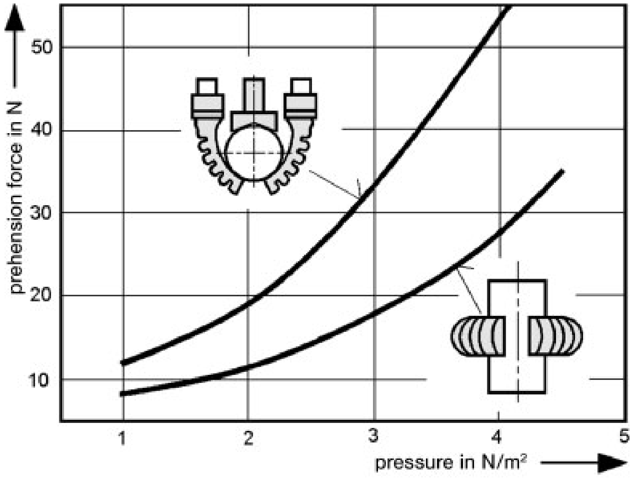


Fig. 8.26: Effective forces typical for elastomeric bending fingers

The spread finger hand depicted in Figure 8.27 possesses three fingers which move towards the gripper centre and enclose the workpiece when vacuum is applied. The vacuum should not exceed 800 mbar. This gripper is suitable for the handling of light workpieces with delicate surfaces. Its design is extremely simple and the formed rubber parts can be periodically replaced.

Tubular springs in the form of *Bourdon tubes,* as employed in pressure gauges, can also be used as torsional actuators for driving impactive gripper jaws. Their cross section can be oval or elliptic. Figure 8.28 illustrates a handling unit designed according to this principle. When pressure is applied the free end of the arm moves outwards along a curved path. Each of the gripper fingers can be opened as pressure is applied, i.e. the fingers can bend open. The extent of the motion is a function of the internal pressure.

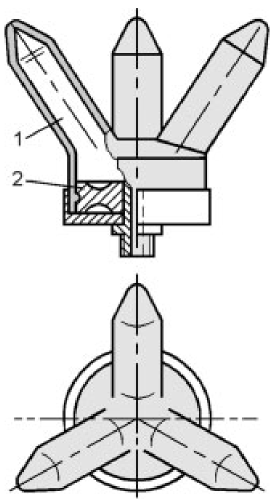
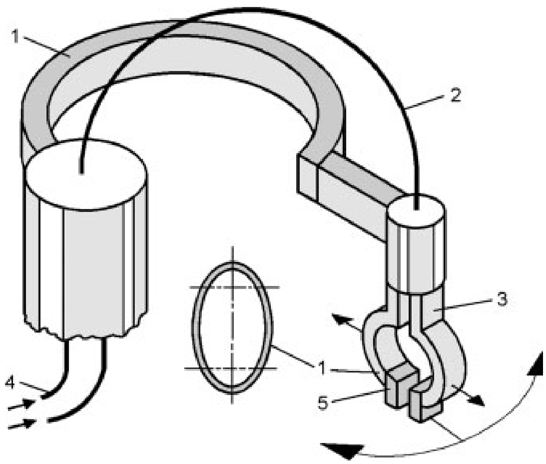


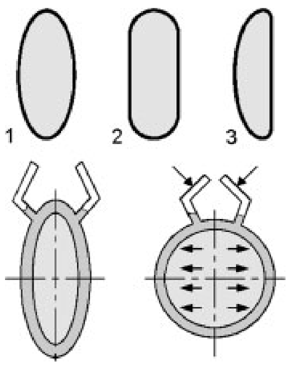
Fig. 8.27: Three-finger spread gripper (*Fipa*)



1 bourdon tube (spring)
2 compressed air line
3 gripper
4 air inlet
5 gripper jaw

Fig. 8.28: Handling unit with *Bourdon* tubes based actuation

Individually controlled gripper fingers can be substituted by structures made from coherent materials. Figure 8.29 shows one such example. Circular expansion of the tubular spring is caused by the application of pneumatic pressure thus causing jaw closure. The tube springs can possess different cross sections and the wall thickness depends on the wide range of internal pressure acting upon the tube spring (typically between 0.6 and 6 bar).



1 eaked oval
2 flat oval
3 flat bow

Fig. 8.29: Gripper structure based on coherent material

8.3 Dextrous Hands

Multi-finger grippers with moving finger links are designed mainly for manipulation tasks requiring a certain amount of dexterity similar to that of the human hand. Hence, these grippers are often called dextrous hands. Such hands have been studied since the early 1980s. Examples include the three-finger hand (thumb and two jointed fingers) developed at the University of Bologna (Italy) [8-10] or the MIT/Utah-Hand [8-11]. Some important steps in this development were already presented in Chapter 1. Some of the designs have been developed further for industrial use, e.g. in remote-controlled manipula-

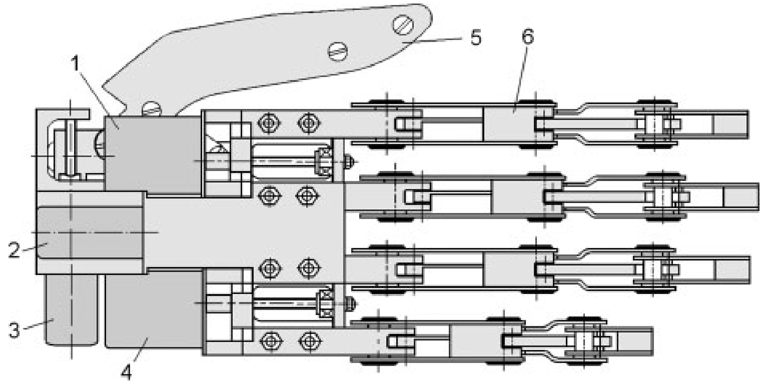


Fig. 8.30: Construction of a 5-finger artificial hand
1 index finger drive, 2 thumb on and off, 3 thumb actuation, 4 actuation of fingers 3 to 5, 5 thumb, 6 jointed fingers

tors for service tasks in dangerous environments or the accomplishment of special medical tasks [8-12]. Much research has been devoted to the development of such hands over the past two decades [8-13, 8-14]. Perhaps their most valuable contribution to technology lies not with the prehension itself but with the development of the necessary micro mechanisms and actuators.

For industrial purposes grippers tend to be more task specific. Usually, the wide flexibility of the human hand is sacrificed in order to produce a gripper deliberately designed to achieve a limited range of tasks better and/or quicker.

Hand prostheses are in many details similar to industrial grippers as can be seen from the artificial hand shown in Figure 8.30 [8-15]. The actuation of the 3-link finger and that of the thumb are integrated into the hand.

Constriction and relaxing of the hand are controlled through electromyograms (EMG) which are taken from the remaining nerve endings of the corresponding hand muscle. Secure prehension of an object requires force reflection. The adjustment of the gripping force can be realized by two control-loops which monitor the corresponding gripper posi-

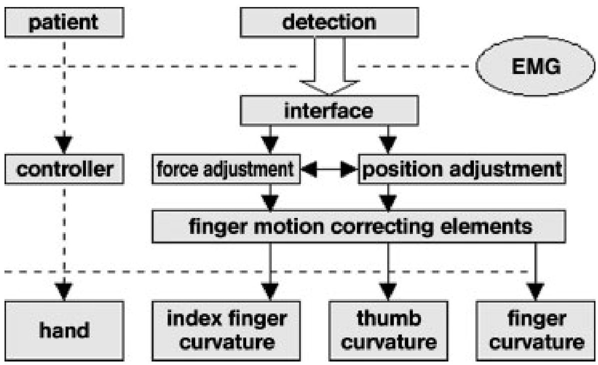


Fig. 8.31: Force adjustment of an artificial hand [8-15]

tion and prehension force. The gripping force is set by slip sensors at the gripping surfaces. The EMG signals allow corrections to be made to the corresponding coordinate elements (gripping motion of the thumb and the fingers). Figure 8.31 shows a control flow scheme.

MH-1 Hand (mechanical hand)
A sensory two-jaw gripper, known also as "Ernst-arm", which was developed by *H. A. Ernst* between 1960 and 1962. It was equipped with approach, tactile, and pressure sensors as well as photodiodes for recognition of approaching objects. The problem studied as a model was the automatic collection of cubes scattered randomly over a surface.

Belgrade Hand
A five-fingered hand modelled on the natural hand (1962), though the finger joints are not independently controllable (Fig. 8.32). When the hand closes, initially each consecutive finger joint moves in the same manner until the finger makes contact with the object. Despite blocked motion of the inner (proximal) finger joints, the outer joints continue to close thus achieving complete enclosure of the object. Problems associated with control of the Belgrade Hand have been drastically simplified [8-16] and several different versions of this hand have been developed over the years.

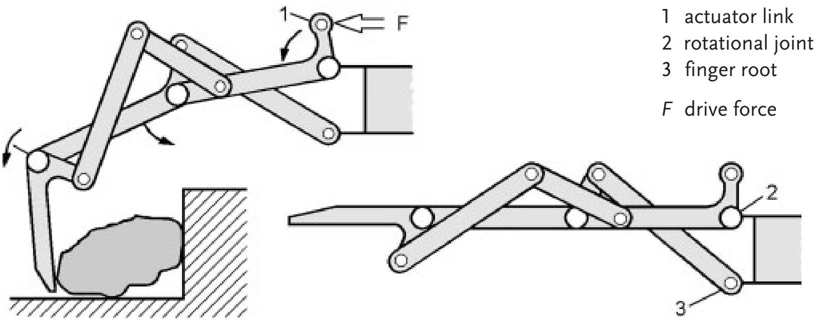


Fig. 8.32: Gripper finger of the Belgrade Hand

Skinner Hand
This hand is a good example for a 3-finger design which enables, the embracing prehension, the spread (internal) prehension, and the two-finger tip prehension (Fig. 8.33). Each finger possesses three joints and in addition can be rotated in the phalanx base. A total of 4 electric motors are employed as prime movers [8-17].

Okada Hand
Three-fingered hand (see Fig. 8.12) developed by a Japanese research laboratory [8-6] possessing 11 joint angle degrees of freedom. The finger positions are reassigned and stored in electronic memory. Intermediate positions are linearly interpolated.

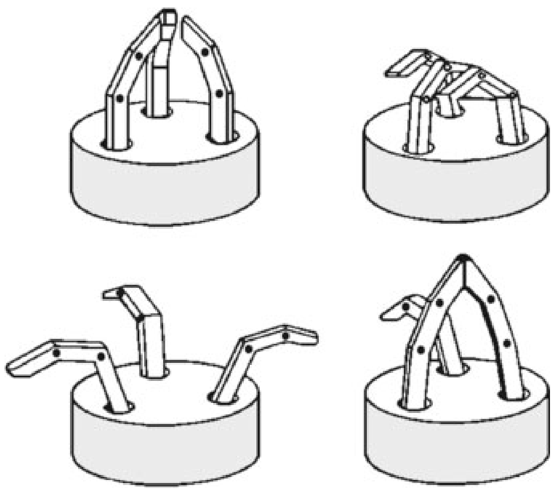
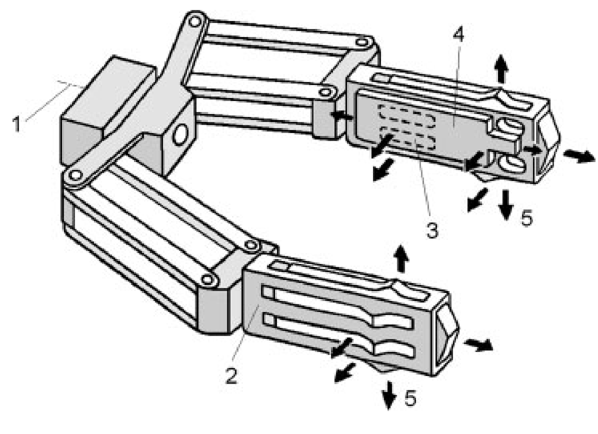


Fig. 8.33: Grip capabilities of the Skinner Hand (1974)

HI-T Hand

This abbreviation stands for the *Hitachi tactile controlled hand*, a gripper designed by the Hitachi Company for assembly work by an industrial robot (Fig. 8.34). This dextrous hand which was developed in 1978 had an elastic hand joint and was capable of completing hole drilling tasks with a tip clearance within 7 to 20 μm in fewer than 3 seconds. 14 contact, 4 pressure, and 6 force sensors were employed. Fine corrective movements were performed by electronically controlled stepping motors. Subsequently (1984), *Hitachi* developed a 3-finger hand with 3 analogous designs [8-18]. Each finger had 3 links and 4 joints but there was no thumb. Actuation was realized using shape memory alloy (SMA) wires which, when electrically heated, contracted against a return spring. This resulted in a relatively high force to weight ratio but, due to the basic thermal principle (heating and cooling sequences) of the actuator, had a somewhat delayed response. Furthermore, it soon became clear that the lifetime of the SMA wire was too short for industrial applications.



1 hand rotation axis
2 gripper finger
3 pressure sensor (pressure sensitive electroconductive rubber)
4 extended sensor plate with limit switch
5 contact sensor

Fig. 8.34: HI-T Hand (Japan, 1978)

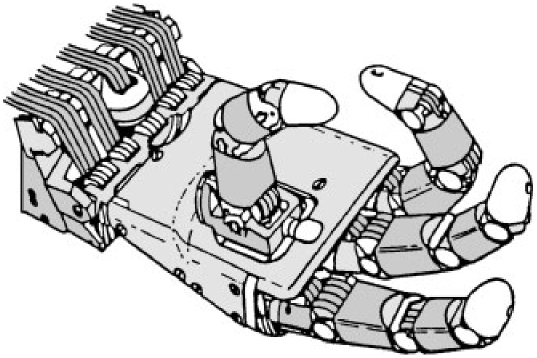


Fig. 8.35: Version IV of the Utah/MIT Hand

Utah/MIT Dextrous Hand

The development of this 4-fingered hand began in 1982 [8-19]. It possesses three fingers and an opposing thumb modelled on the human hand (Fig. 8.35). The finger enjoys 16 degrees of freedom.

The finger links are actuated by tension bands. The finger designs are shown in Figure 8.36. Since ropes and bands can transmit only tension, two bands were necessary for each finger link. This makes a total of 32 tension bands ("sinews") for the 3 fingers and the thumb, which must be guided through a correspondingly large number of pulleys. The pneumatic drive cylinders are not integrated with the hand but housed externally in the forearm, which leads to some limitations. The fingers are electrically controlled by means of relatively computationally intensive software.

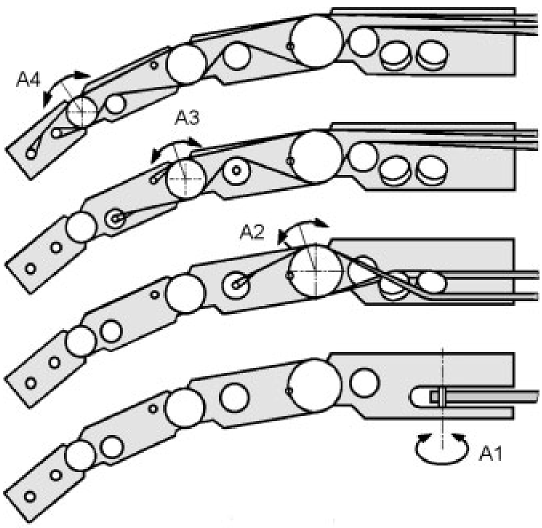


Fig. 8.36: Guiding of the tension bands (superhard plastics) in a finger with 4 degrees of freedom (Utah/MIT Dextrous Hand)

A motion axis

Stanford/JPL Hand (Salisbury Hand)
A three-fingered hand (Fig. 8.37) with opposing thumb which comprises 9 degrees of freedom for the three joints per finger. Finger motion is based on 12 Teflon covered cables driven from 12 miniaturized DC motors with microprocessor control mounted in the robot forearm. Sensors determine driving force from the cables and encoders the rotation angle. The finger tip joints are augmented with 8 × 8 tactile sensor arrays [8-20].

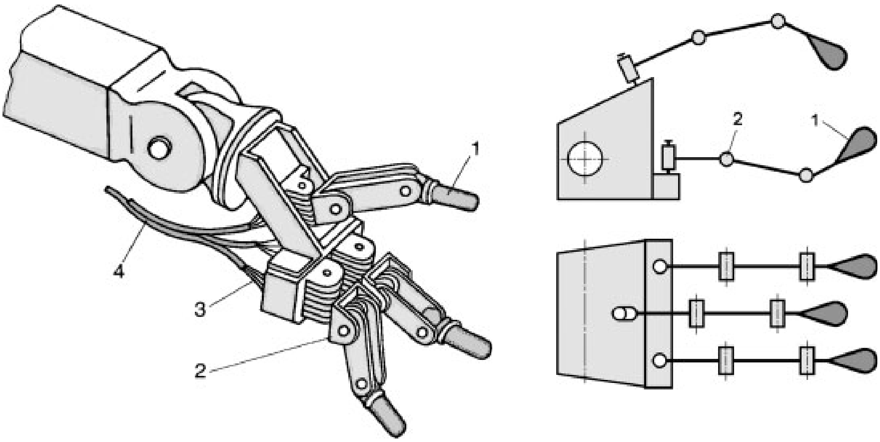
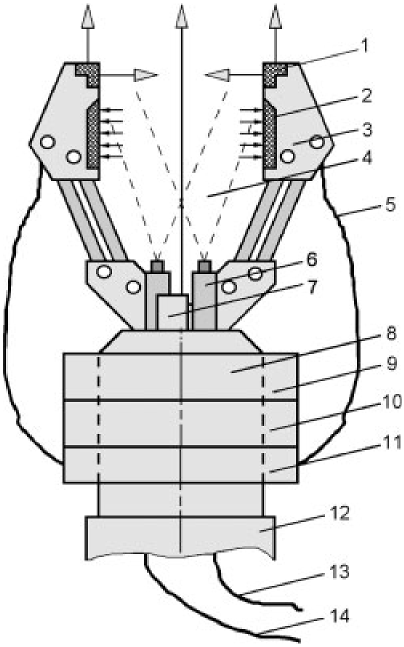


Fig. 8.37: Stanford/JPL Hand (1983)
1 grasping organ, 2 joint, 3 pull cable, 4 pull cable cladding

DLR Gripper (Rotex Gripper)
A two-fingered gripper from the German Aerospace Institute (DLR) intended for space research in the ROTEX (**R**obot **T**echnology **E**xperiment). The device (Fig. 8.38) possesses sophisticated sensors: 16 “grope” sensors in each of the two opposing gripper jaws, two miniature cameras for control of approach and nine additional laser based sensors. The gripper comprises several hundreds of mechanical and thousands of electronic components. It is remotely controlled from the earth using a dataglove.

Darmstadt Hand
This hand, developed in the Technical University Darmstadt (1993), only slightly resembling the human hand, possesses 3 star-arranged fingers each containing 3 joints. The joints are actuated by motor driven (harmonic drive servo) cables. It is assumed that the control can be realized by means of a trained artificial neural network. The joint position and the current moment can be measured in each of the 9 joints. With appropriate regulation of the entire system it is possible to selectively move tools within the gripper using programmed forces. Possible applications include nuclear technology, underwater and space exploration.



1 close-up range finder
2 tactile arrays
3 gripper jaws
4 field of vision
5 signal transmission
6 stereo cameras
7 distant object range finder (scanner)
8 integrated gripper mechanics
9 elastic force/torque sensor (instrumented compliance)
10 rigid force/torque sensor
11 range finder electronics
12 manipulator arm
13 control lines (20 kHz bandwidth)
14 serial bus

Fig. 8.38: Multisensor manipulator design from DLR which flew aboard the US space shuttle *Columbia* in 1993

TUM Hand

A three-fingered hand developed at the Technical University Munich (Germany) in 1994 by *F. Pfeiffer, R. Menzel and K. Woelfl*. The shape and degrees of freedom of this design are based on the human jointed finger model. Actuation is realized using miniaturized hydraulic cylinders fixed directly to the fingers (Fig. 8.39). Each finger possesses four joints which enables lateral tilt and bend motions. The outermost bending joints are coupled together as in the Belgrade Hand. The round finger tips are equipped with pressure sensors.

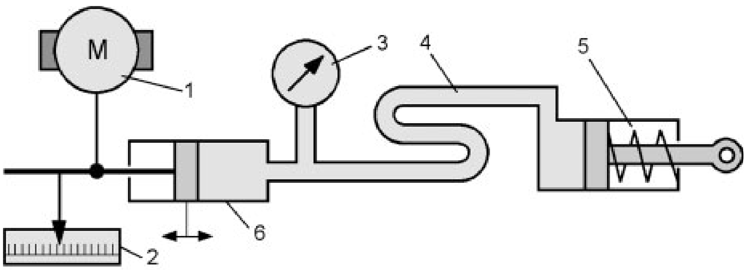


Fig. 8.39: Hydraulic system for a finger joint drive of the TUM Hand
1 electric motor, 2 position sensor (potentiometer), 3 pressure sensor, 4 hydraulic tube, 5 finger joint cylinder with integrated return spring

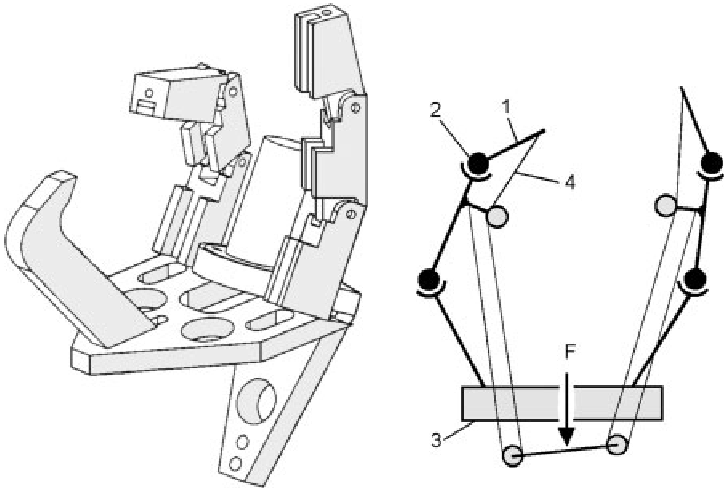


Fig. 8.40: WBK Hand (Karlsruhe University, Germany, 1997)
1 finger link, 2 joint, 3 mechanical base, 4 sinew (chord), *F* tension force

WBK Hand
An anthropomorphic hand which, however, exhibits only two jointed fingers and a fixed thumb (Fig. 8.40). The transmission of the driving force is achieved using high-strength polymer cords. The topology of the object is used to match the fingers which are reset by torsion springs housed within the joints. Only one actuator is required and control is relatively simple. In comparison with other hands, the flexibility of the WBK Hand is limited but costs are considerably lower. By means of a balance, the forces are distributed symmetrically over all finger links which ensures optimum prehension for any arbitrary object geometry [8-21].

DLR Hand II
A four-fingered anthropomorphic hand developed for service robots around 2001: this hand has 13 degrees of freedom, 112 sensors, about 1000 mechanical and 1500 electronic components, a maximum finger tip force of 30 N, 12 interfaces (leads), and a total mass of 1800 g. Each finger possesses 3 independent degrees of freedom and 4 joints.

An additional degree of freedom in the palm makes it possible to adapt and optimise the hand for stable grip or to fine manipulation requirements. Drivers and sensors are completely integrated into the hand and it is possible to manoeuvre $F = 13$ degrees of freedom. Figure 8.41 shows a single spindle drive with shaft joint for the finger. The high speed rotation of a miniature electric motor is transformed into linear motion by a planetary roller gear [8-22].

Karlsruhe Hand
A three-fingered hand developed for research purposes and in particular for object slippage studies. Figure 8.42 shows one finger of this hand. The finger grasps concentrically towards the centre [8-23]. The *Karlsruhe Dextrous Hand II* is a robot gripper with four fin-

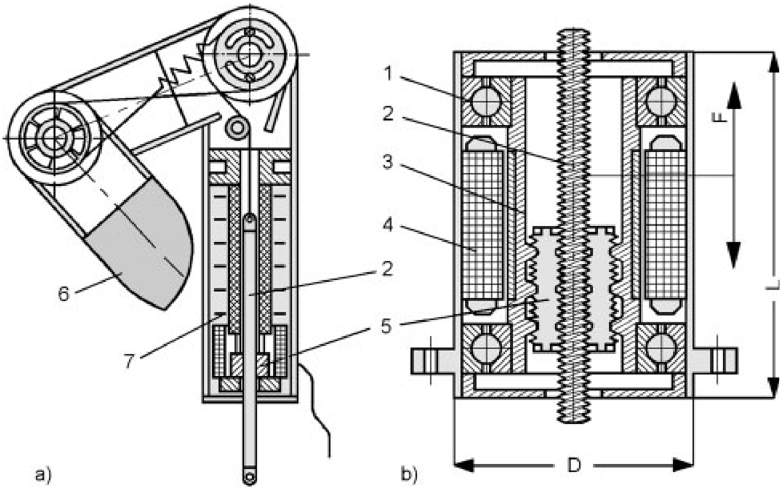
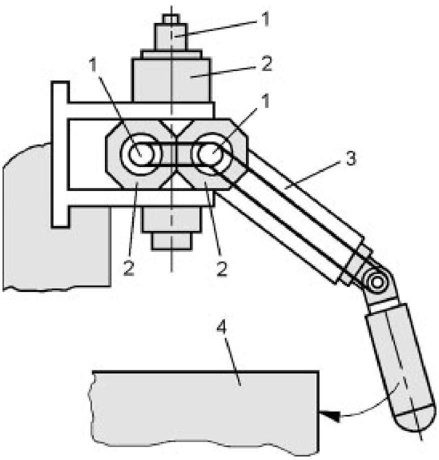


Fig. 8.41: Bending finger and DLR planetary roller spindle drive (*Wittenstein*)
a) finger with integrated planetary roller drive, b) "Artificial Muscle" AM 20
1 ball bearing, 2 fine thread spindle with, e.g., 0.2 mm thread pitch, 3 spindle nut,
4 brushless DC motor, 5 planetary roller, six radially distributed rollers
$D = 21$ mm, $F = 300$ N, $L = 58$ mm

gers and three degrees of freedom for each of them [8-24]. The basic concept corresponds to the first version, hence the hands ability to grasp irregularly shaped objects in assembly operations. For this purpose the finger tips are equipped with force sensors enabling the hand to rotate objects between the finger tips. Actuation is realized by DC motors and ball spindle gears. In order to register the spatial position of the object under prehension, the hand is provided with laser triangulation sensors. The entire system is capable of real time operation enabling it to detect and react to unpredictable movements of the object.



1 DC motor
2 gear
3 toothed belt
4 gripped object

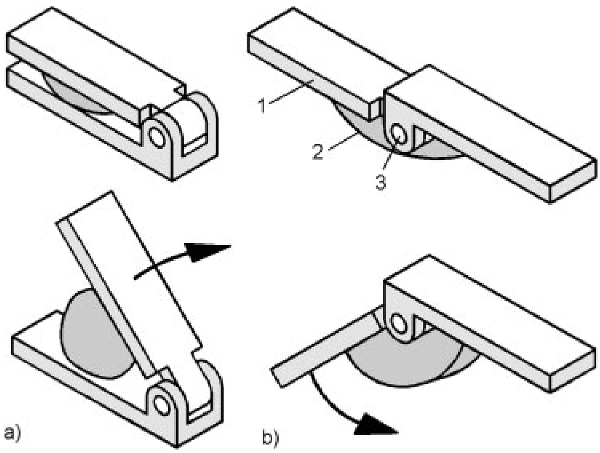
Fig. 8.42: Finger of the Karlsruhe Hand

IFAS Hand

An anthropoid servopneumatic hand developed in the Institute of Fluid Power Drives and Controls (IFAS) of the Aachen University of Technology (RWTH), Germany, by a team lead by the Taiwanese engineer Chung Fang. Like most dextrous hands, it is not a commercially available product and one and a half times larger than the human hand. The joints in the thumb and the three fingers are actuated by compressed air. The hand possesses a total of 11 servopneumatic joints as well as pressure sensors for retention force regulation and an angle sensor for precise finger positioning. The hand is amazingly dextrous [8-25] and is presently being used in basic research. It is capable of clamping a ball between the thumb and the middle of the three fingers and rotating it by the other two fingers without changing its position.

FZK Hand

The joints of this five-finger hand from the Information Technology Research Centre, Karlsruhe University (FZK), Germany, are driven by 18 micro-fluid (gas) actuators. The inflation of small flexible chambers, mounted in the joints, leads to their expansion and opening of the joint. Weighing only 860 g (including shaft, battery, protective glove and pneumatics), the hand is considerably lighter than its electromechanical counterparts. With this hand it is possible, for the first time ever, to achieve the five most important prehension strategies (described in Section 2.2.1). The designer (*Stefan Schulz*) envisages such applications as prostheses [8-26, 8–27]. Figure 8.43 shows the operational principle of such flexible pneumatic actuators. Driven by compressed air with a pressure of 3 to 5 bar they can achieve forces of up to 10 N for stretch or bend movements with frequencies of up to 10 Hz. Incidentally, flexible actuators were described as early as 1872 by *Franz Reuleaux* (1829–1905) who worked in the then Royal Technical College of Berlin.



1 swivel plate
2 flexible fluid chamber
3 axial pin

Fig. 8.43: Flexible fluid actuator (Institute for Applied Computer Science (IAI), Karlsruhe, Germany)
a) expansion, b) contraction

The biomechanics employed in the drive hydraulics of spider legs should be viewed in the same context. From tarantulas to dust mites, all arachnia possess fluid channels between their stretching muscles, which transmit the contraction force of the forebody in the form of pressure, thus exerting a turning moment on specially designed joints.

Robonaut Hand

The word robonaut stands for *robotic astronaut* which is a *telepresence*-robot with a height of 1.9 m and a mass of 182 kg, designed for space missions [8-28]. This robot is expected to support future astronauts in maintenance and repair work in space. For this purpose it was necessary to develop a hand, the size and appearance of which mimics the human hand. The Robonaut Hand (NASA) is a five-jointed finger hand with 22 degrees of freedom. 14 joints can be independently activated. Much importance was attached to stability against large thermal fluctuations, which are typical for space conditions. Possible outgasing of hand components in vacuum and their effect on the other aerospace systems have also been taken into consideration. The hand possesses encoders mounted directly in the joints and motors. It is capable of directly acquiring and turning a screwdriver, or manipulating tweezers in order to grasp very small objects.

Further dextrous hand implementations of varying complexity [8-29] are still being developed for educational and investigative purposes, mainly in research institutions, colleges and universities: some examples include the five-finger hand of the Technical University Berlin, Germany, the Gifu 5-jointed finger hand of the Gifu University (Japan), the IPA Hand (*IPA*, Stuttgart, Germany) with fixed thumb and two movable fingers [2-15], a hand with tactile sensors on rounded finger ends in order to produce a “finger tip feeling” (University Bielefeld, Germany) and several variations of hand from ETH Zurich, Switzerland, and other institutes.

9
Hand Axes and Kinematics

Hand axes are assembly groups which enable the spatial orientation of a gripper through rotational or translational motion. These axes, together with the gripper, constitute a complete kinematic chain. The wrist axes of industrial robots are normally an integral part of the final transformation of this kinematic chain. However, in the special machines and dedicated manipulators, wrists may be an integrated part of a specialized gripper.

The first wrist structures were developed in the mid 1940s in *Argonne National Laboratory* for the handling of radioactive materials. Multiaxial wrists were studied in the 1960s in connection with the design of operating automated spray-painting and arc welding industrial robots. Three-axis robot wrists can be divided into two categories depending on the orientation of their axes:

- RPY (pitch – yaw – roll)
- Euler (roll – pitch – roll)

The notations used for the three degrees of freedom are taken from nautical terminology, though they also correspond to movements of the human hand (Fig. 9.1).
An extensive presentation of design possibilities for wrist axes can be found in [9-1].

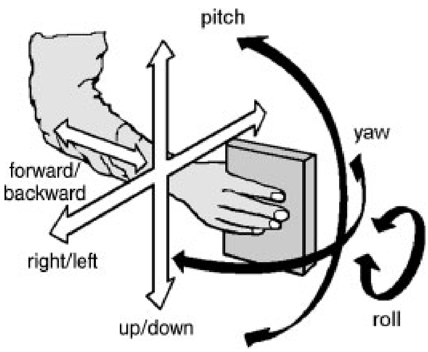


Fig. 9.1: Basic human wrist mobility

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

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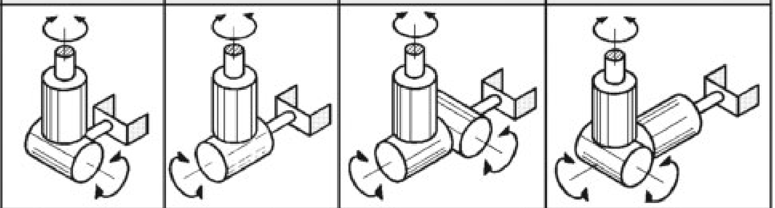
9.1 Kinematic Necessities and Design

Grippers can be provided with hand axes in order to better satisfy process requirements and spatial orientation can be described by three angles. Consequently, 3 degrees of freedom are necessary in order to achieve any arbitrary wrist orientation. This also means that 3 drives must be available. However, one or two hand axes are often sufficient. Figure 9.2 gives a basic overview of the arrangement of hand axes.

hand axis structure	RR	RT	RTR	RRT
axis configuration (selection)				

angle of rotation	0°...100°	90°	+90°...-90°	180°	360°	arbitrary
axis actuation	manual	pneumatic		hydraulic	electric motor	
motion sequence	one after the other		simultaneously superimposed		simultaneously mechanically coupled	

Fig. 9.2: Technical characteristics of typical wrist axes
R rotation joint, T torsion joint

Any wrist structure can be associated with one of the kinematic structures presented in Figure 9.3. The underlying feature used for this differentiation is the spatial orientation of the rotational axes.

The three rotational axes cross or intersect either pair-wise or all together at a single point. In view of the simplest possible control algorithm for the positioning of the gripper at the workspace destination, it is preferable to have one common intersection point of the three rotational axes and two equal intersection angles (δ_1, δ_2).

In general, for the case depicted in Figure 9.3 a, the workspace obtained with respect to link 4 is at point A. The form and the mass depend on the kinematic dimensions of the wrist chain and the rotation angles of the axes. In practice, the motion ranges are limited by the presence of power and signal lines rather than the joint mechanics. Wrist designs vary primarily according to the mechanical dimensions of drive, gear and bearing components.

An additional link z is introduced into the open kinematic chain of the design shown in Figure 9.3 d and the two neighbouring links are coupled with each other over a pinion gear. In such a way driven rotation inevitably produces rotation of the subsequent links about some temporary axis of rotation. Given multiple branching of this kind the resulting wrist resembles a trunk, as can be seen from the method depicted in Figure 9.4 (see also Fig. 7.5).

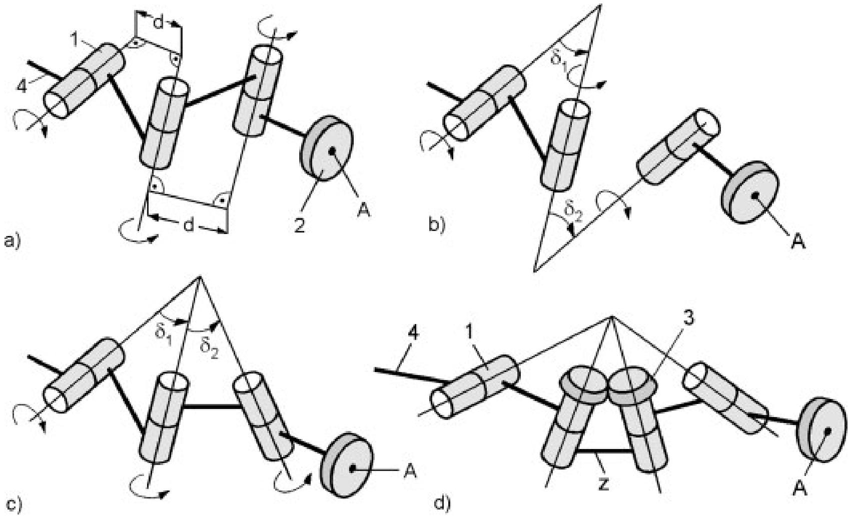
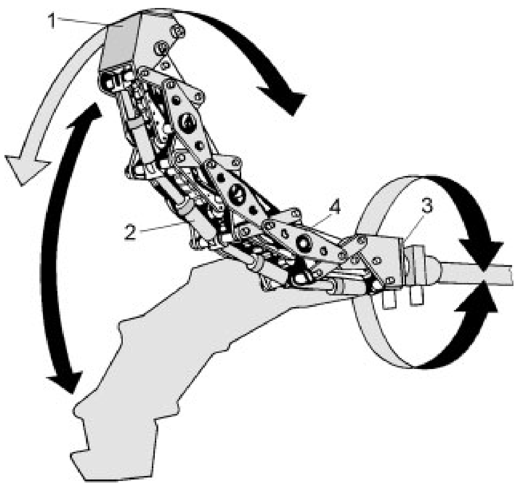


Fig. 9.3: Kinematic structures of wrists with 3 rotational axes ($F = 3$)
a) wrist with crossing axes, b) wrist with pair wise intersecting axes, c) axes intersecting at one point, d) structure with axes intersecting at one point and additional branching of the kinematic chain
1 swivel joint, 2 gripper connection flange, 3 pinion, 4 robot forearm, A = TCP of the flange, δ crossing and intersecting angle respectively, d crossing distance, z additional link



1 endeffector connection flange
2 fluidic joint drive
3 handling equipment connection flange
4 mechanical joint chain

Fig. 9.4: Trunk-like wrist structure with 2 degrees of freedom (Nitro-Nobel-Mec.)

Modular systems allow the combination of wrists in accordance with technological requirements. However, the modules must be compatible, and work together with other modules within the same system. Figure 9.5 shows several designs for such a case schematically. The coupling of these components for the example shown is realized by dovetail clamping elements. Such coupling elements are to a large extent vibration-safe for small loads. As can be seen, it is possible to use both additional rotational and translational axes. Thus, it is possible to design double, multiple and turret grippers.

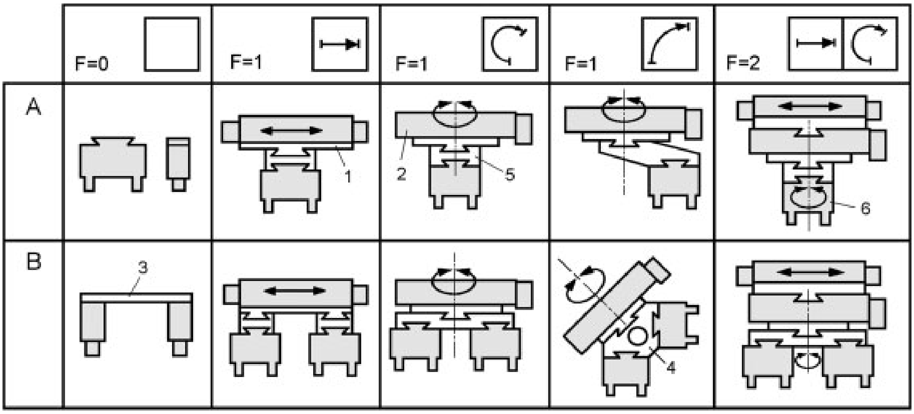


Fig. 9.5: Kinematic upgrading of a main gripper
A single gripper, *B* double gripper, *F* degree of freedom
1 short travel unit, 2 pivot unit, 3 connection plate, 4 angle, 5 mechanical interface, 6 gripper

Grippers are often connected to rotary units through a pivot arm. The physical size of the rotary and pivot units must be chosen in such a way that the eccentric loads can be easily managed. The manufacturers offer relevant power diagrams from which limits for the mass moment of inertia, pivot angle, and pivoting time can be deduced. Initially it is necessary to calculate the mass moment of inertia for the components to be attached to the rotational drive. One typical example is described with the help of Figure 9.6.

When computing the mass moment of inertia it should be noted that, for the given example, only the intermediate disk has its centre of mass directly on the rotational axis, if it is not an integral part of the rotation drive. All other masses outside the Z-axis are represented by point masses with separations corresponding to the centres of inertia, and the torque is reduced to the rotational drive axis. Only in that case it is justified to add the mo-

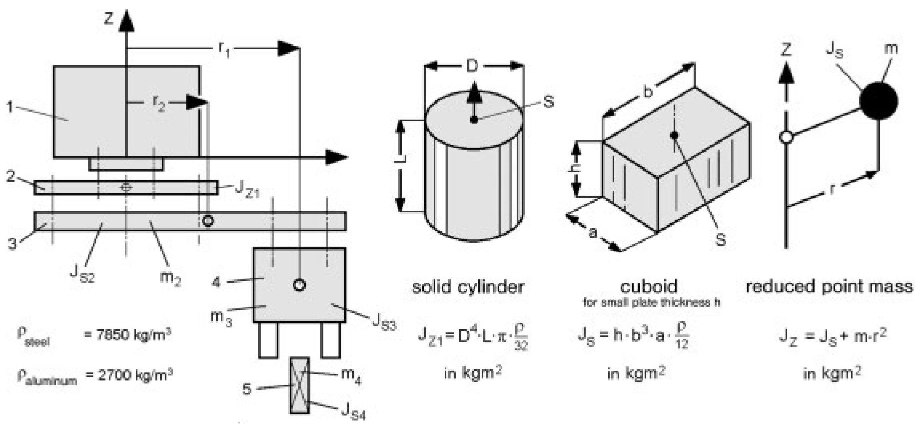


Fig. 9.6: Rotation unit with pivot arm and gripper
1 rotational drive, 2 intermediate disk, 3 pivot arm, 4 gripper, 5 workpiece
S barycentric axis, *m* mass, *r* radius, *J* inertial torque, ρ density

ments of inertia. This procedure is called "*Steiner's theorem*". According to which, the axial angular impulse is given by:

$$J = J_x + A \cdot \alpha^2 \qquad [\mathrm{cm}^4] \tag{9.1}$$

J_x axial angular impulse [cm^4]
α separation of the two axes [cm]
A area [cm^2]

The total mass moment of inertia J_{ges} of the attached components for the given example is obtained in general from:

$$J_{ges} = J_{Z1}\ (\text{disk}) + J_{Z2}\ (\text{arm}) + J_{Z3}\ (\text{gripper}) + J_{Z4}\ (\text{workpiece})$$

J_z mass moment of inertia with respect to the Z-axis

Since some of the moments must be converted to the Z-axis equation (9.2) is obtained:

$$J_{ges} = J_{Z1} + J_{S2} + m_2 \cdot r_2^2 + J_{S3} + m_3 \cdot r_1^2 + J_{S4} + m_4 \cdot r_1^2 \tag{9.2}$$

J_S mass moment of inertia relative to the centre of gravity S of the body

Using the value of J_{ges} obtained from the calculation, depending on the pivot angle to be used (e.g. 180°), the achievable pivoting time can be ascertained from the manufacturer's power diagram. For the example presented it remains to verify whether the forces related to the masses can be tolerated by the rotational drive. The bearings of this unit are designed for a definite maximum load which should not be exceeded. The allowed axial load in the Z-axis (for the given example) can simply be found from the manufacturer's data.

Example: What is the maximum load sustainable by the handling equipment employed for the application shown in Figure 9.7.

Dimensions:
$D = 50$ mm, $L = 6$ mm, $L1 = 145$ mm, $L2 = 25$ mm, $L3 = 80$ mm
$b = 22$ mm, $d = 40$ mm, $h = 6$ mm, ρ (steel) = 7850 kg/m^3, ρ (alu) = 2700 kg/m^3

Remark: The composition of steel and aluminium components as assumed in this example is not always to be recommended. Their thermal expansion coefficients deviate strongly and the possible reaction $FeO_2 + AI \rightarrow Fe + AlO_2$ could cause problems over long times. As a rule combinations of metals and plastics, if sufficiently stable, are preferable.

Initially the separate moments of inertia with respect to the Z-axis must be determined. Insignificant features related to the shape of the components, as e.g. threaded holes, can be neglected. The gripper fingers will also not be considered here. The mass moment of inertia J_{s3} of the gripper can be taken from the gripper manufacturer's data.

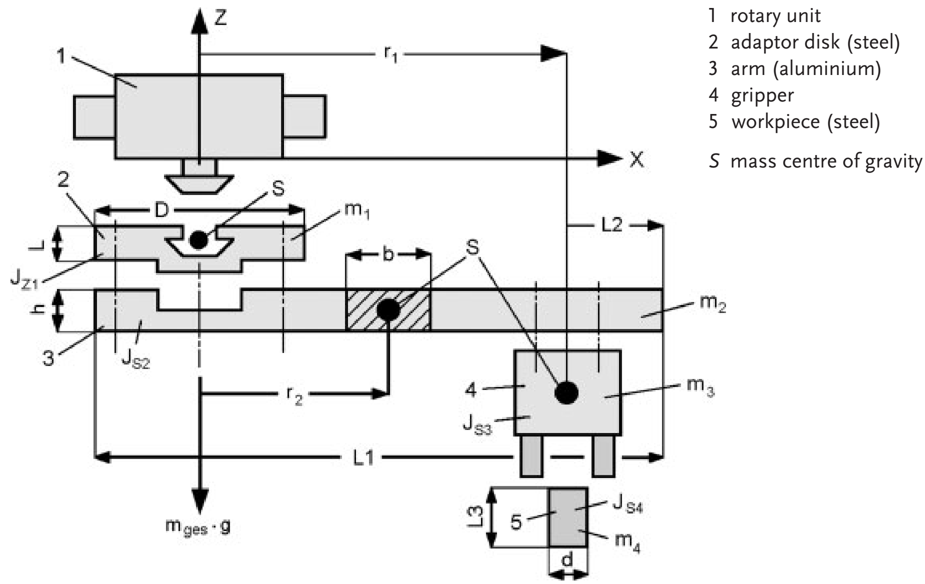


Fig. 9.7: Example of a conceptual formulation

$$J_{Z1} = \frac{\pi \cdot D^4 \cdot L \cdot \varrho}{32} = \frac{3.14 \cdot 0.05^4\,\text{m}^4 \cdot 0.006\,\text{m} \cdot 7850\,\text{kg}}{32\,\text{m}^3} = 2.87 \cdot 10^{-5}\,\text{kg m}^2$$

$$J_{S2} = \frac{h \cdot L_1^3 \cdot b \cdot \varrho}{12} = \frac{0.006\,\text{m} \cdot 0.145^3\,\text{m}^3 \cdot 0.022\,\text{m} \cdot 2700\,\text{kg}}{12\,\text{m}^3} = 9 \cdot 10^{-5}\,\text{kg m}^2$$

$$J_{S3} = 4.4 \cdot 10^5\,\text{kg m}^2$$

$$J_{S4} = \frac{\pi \cdot d^4 \cdot L3 \cdot \varrho}{32} = \frac{3.14 \cdot 0.04^4\,\text{m}^4 \cdot 0.08\,\text{m} \cdot 7850\,\text{kg}}{32\,\text{m}^3} = 14.71 \cdot 10^{-5}\,\text{kg m}^2$$

Since only the moment of inertia of the adaptor disk J_{Z1} relates to the rotation axis Z, the other moments of inertia, which were calculated on their axes through the mass centre, should be considered in accordance with the *Steiner's theorem*. The moments of inertia may then simply be added together. In each case it is necessary to know the mass of the corresponding component, for which the following relation is valid:

$$m_1 = \frac{D^2 \cdot \pi}{4} \cdot L \cdot \varrho = \frac{0.05^2\,\text{m}^2 \cdot 3.14}{4} \cdot 0.006\,\text{m} \cdot \frac{7850\,\text{kg}}{\text{m}^3} = 0.0924\,\text{kg}$$

$$m_2 = L1 \cdot b \cdot h \cdot \varrho = 0.145\,\text{m} \cdot 0.022\,\text{m} \cdot 0.006\,\text{m} \cdot \frac{2700\,\text{kg}}{\text{m}^3} = 0.0516\,\text{kg}$$

$m_3 = 0{,}185\,\text{kg}$ (taken from the corresponding gripper catalogue)

$$m_4 = \frac{d^2 \cdot \pi}{4} \cdot L \cdot \varrho = \frac{0.04^2\,\text{m}^2 \cdot 3.14}{4} \cdot 0.08\,\text{m} \cdot \frac{7850\,\text{kg}}{\text{m}^3} = 0.7887\,\text{kg}$$

The total moment of inertia being obtained from equation (9.2)

$$J_{\text{ges}} = 2.87 \cdot 10^{-5} + 9 \cdot 10^{-5} + 0.0516 \cdot \left(\frac{0.145 - 0.025 - 0.025}{2}\right)^2 + 4.4 \cdot 10^{-5} + \ldots..$$

$$\ldots + 0.185 \cdot (0.145 - 0.025 - 0.025)^2 + 14.71 \cdot 10^{-5} + 0.7887 \cdot 0.095^2 = 0.0092\,\text{kg m}^2$$

It remains to be checked whether the rotary unit is capable of sustaining the forces in the Z-axis. The allowed bearing load can also be taken from the manufacturer's data. The following relation holds:

$$F_Z = m_{\text{ges}} \cdot g \tag{9.3}$$

$$m_{\text{ges}} = m_1 + m_2 + m_3 + m_4 \tag{9.4}$$

With the values specified in the example, the final force obtained is:

$$m_{\text{ges}} = 0.0942\,\text{kg} + 0.0516\,\text{kg} + 0.185\,\text{kg} + 0.7887\,\text{kg} = 1.117\,\text{kg}$$

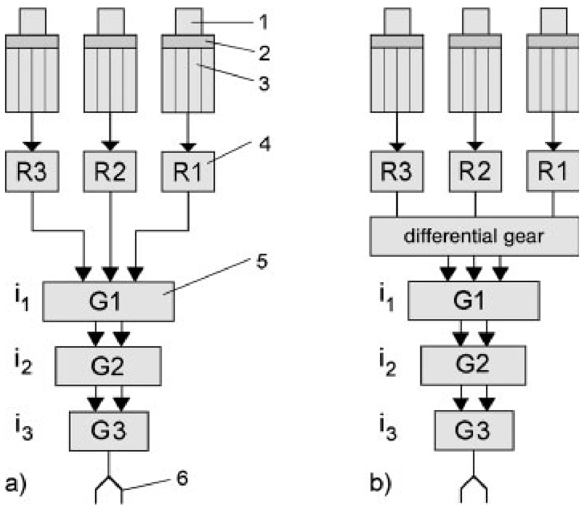
$$F_Z = 1.117 \cdot \text{g} = 1.117\,\text{kg} \cdot 9.81\,\text{m/s}^2 = 10.06\,\text{N}$$

9.2 Rotary and Pivot Units

In the case of fully articulated 6 axis industrial robots the wrist kinematics are integrated with the rest of the manipulators kinematics. Control is coordinated via computer using a high level language such as *Fanuc's* KAREL or *Stäubli-Unimation* V+ (a VAL II derivative). The remainder of this chapter is relevant to other cases where no such high level control is available and the user must implement his or her own design in conjunction with the prehension system.

It is possible to decouple the hardware associated with the different motions by interposing a differential gear. Thus, each of the three rotational motions will be realized by a separate drive motor. The principle of such structures is shown in Figure 9.8.

The differential gear shown in Figure 9.9 is an example of kinematic decoupling of the two axes of a wrist gear. Pivoting and rotation are coupled. Rotation of the gear wheels Z_1 and Z_2 in the same direction (relative to the motor) and with the same angular velocity results in rotational motion of Z_3 and consequently rotation of the gripper (hand pivoting). If the rotation is with the same velocity but in different directions the hand will rotate solely about the longitudinal axis (hand rotation). Arbitrary rotations of the toothed wheels result in a superposition of pivoting and rotational motions.



1 angle encoder
2 tachogenerator
3 electric motor
4 speed reducer
5 complementary gear stage
6 gripper

i_i gear ratio

Fig. 9.8: Principles governing wrist structure in terms of motion coupling
a) coupled motions
b) decoupled motions

The following relationships are valid for the kinematic coupling example of Figure 9.9 with gear wheel pairs possessing a reduction factor u when only two motions (hand rotation and hand pivoting) are present [9-2]:

$$\dot{\theta}_1 = \frac{1}{u}\Omega_1 - \frac{1}{u}\Omega_2 \tag{9.5}$$

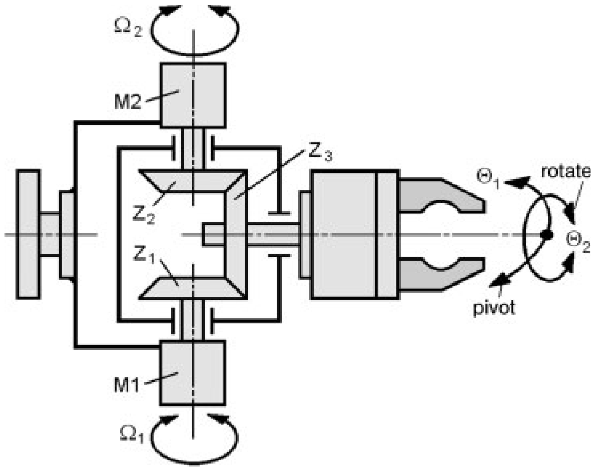
$$\dot{\theta}_2 = \frac{1}{u}\Omega_1 - \frac{1}{u}\Omega_2 \tag{9.6}$$

$$\dot{q} = S_G \cdot \overline{\Omega} = \frac{1}{u}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \cdot \overline{\Omega} \tag{9.7}$$

$\dot{\theta}$ joint angular velocity
S_G gear matrix
$\overline{\Omega}$ vector motor angular velocity
u gear reduction factor
θ joint angle
$\dot{q}$ velocity vector
Ω angular velocity

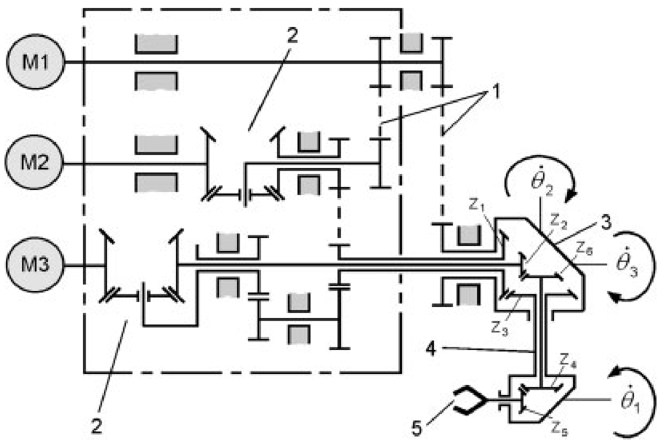
Figure 9.10 shows a hand axis gear with decoupled hardware. There are only three rotational hand axes, with angular velocities $\dot{\theta}_1$ to $\dot{\theta}_3$.

If the coaxial shaft (4) rotates relative to the housing (3) with a velocity $\dot{\theta}_2$, then gear wheel Z_5 will also rotate against gear wheel Z_4 resulting in an unintended gripper rotation ($\dot{\theta}_1$). In order to avoid this it is necessary that, with motor M2 switched on, wheel Z_4 rotates synchronously with the coaxial shaft (4). This requires that wheel Z_1 is coupled to wheel Z_4



Z pinion
M drive motor

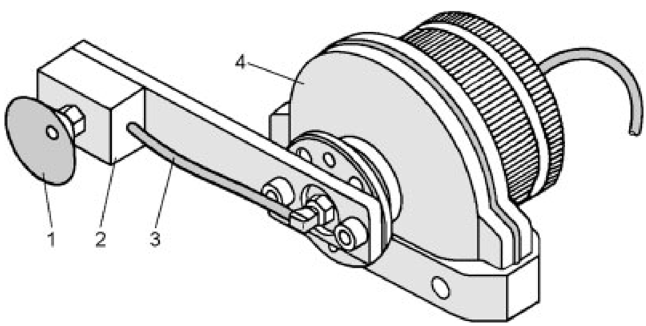
Fig. 9.9: Gripper with a differential gear for rotary and pivot hand functions



1 toothed belt transmission
2 differential gear
3 housing
4 coaxial shaft
5 gripper

M drive motor
$\dot{\theta}$ angular velocity
Z number of teeth

Fig. 9.10: Differential gear for actuation of a robot hand



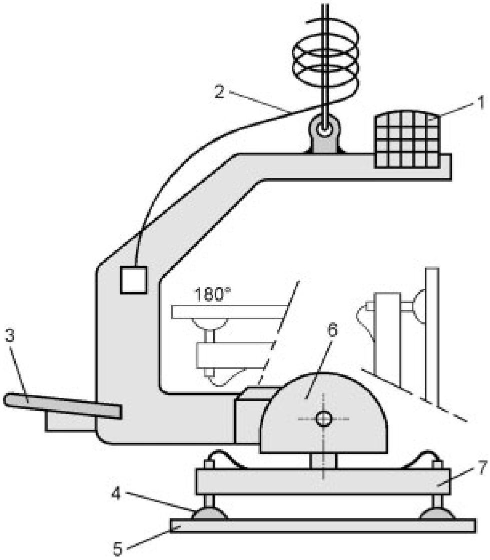
1 suction cap
2 ejector
3 compressed air line
4 rotational pneumatic drive

Fig. 9.11: Swivel suction unit (*Festo*)

with the same transmission ratio. A differential gear ensures the synchronous rotation of Z_1 and Z_4 while the motors M1 and M3 remain stationary [9-3].

In practice there are many simpler designs, especially in cases where only one rotational axis is sufficient. Figure 9.11 shows a suction gripper with a pivoting axis intended for simple pick-and-place tasks.

The following application example demonstrates a vacuum suction gripper which is attached to a wire balancer or an electric chain hoist. The objects are acquired from the hor-



1 vacuum pump
2 electric cable
3 guiding grip of the manipulator
4 suction cap
5 workpiece
6 electric motor and gearbox
7 cross-beam

Fig. 9.12: Suction gripper with 180° swivel axis

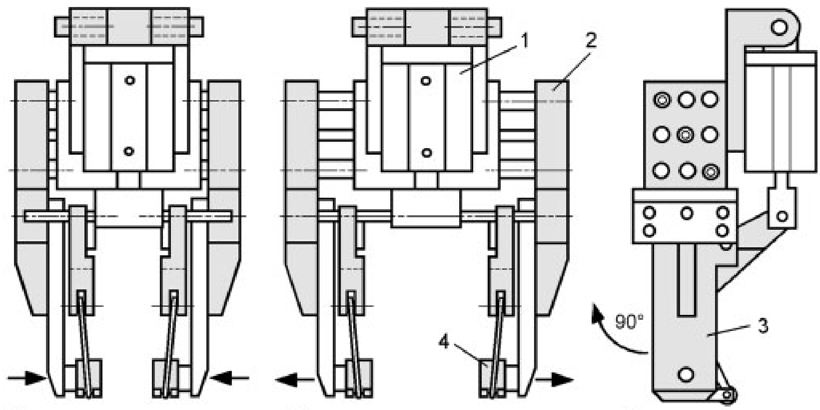


Fig. 9.13: Swivel gripper with additional rotation (*IPR*)
a) gripper closed, b) gripper open, c) side view
1 pneumatic cylinder, 2 parallel jaw gripper, 3 gripper finger, 4 gripper jaw

izontal plane. The gripper can be moved by an electric motor driven rotational axis by 90° or 180° (Fig. 9.12).

It is also possible to control intermediate positions, for example the rotation of the workpiece (glass panel, plywood plate, etc.) into a vertical position. This usually requires a slightly inclined position of about 82°.

Recent developments in prehension technology include grippers employing additional finger rotation. Figure 9.13 shows one such design. Applications include operations where a defined angle exists between the acquisition and deposition planes. The design is based on a reliable parallel gripper with an attached pneumatic pivot drive.

10
Separation

10.1
Separation of Randomly Mixed Materials

Picking randomly orientated parts from a bin is a generic problem almost as old as the field of robotics itself [10-1]. In recent years the problems associated with individual object identification and orientation using sophisticated vision techniques has been largely bypassed by the use of vibratory feeders [10-2]. This is satisfactory for rigid components possessing consistent features thus ensuring ease of positioning. However, mixed objects of a non-rigid nature suffer from a number of additional problems which not only make them difficult to feed automatically but can cause severe entanglements. In the absence of a gripping technique which, by its prehensive nature, is able to discriminate between object or material types, sensory identification followed by other means of selective prehension is needed.

When automatically selecting a single item from a randomly mixed heap of identical objects, the probability of acquiring two or more such objects is proportional to the stroke of the endeffector. This is intuitively obvious when one considers the removal of a single item, such as a paper clip, from a box full. Using the full span of the fingers is likely to yield a handful of clips, whereas closure over a small distance between two fingers is more likely to result in the selection of a single item. This is also true with any robotic acquisition technique and the problem is further exacerbated when the heap consists of articles of varying size, material and relative quantities. The term stroke normally refers to the uni-dimensional distance of closure between two gripper jaws. However, three or four jaw "chuck" type grippers have a stroke which spans a two dimensional field, as do most contigutive prehension methods. Furthermore, the field of influence of surface permeating prehension methods, such as vacuum suction and magnetoadhesion, can be considered to have three dimensional volumetric strokes.

The ideal is a combination of high gripping force over a very small stroke. Clearly, this is rarely attainable in practice and so must be reduced to the optimum capability under the prevailing circumstances. This can usually be achieved by a combination of two or more of the prehension techniques previously described. The initial prehension by contigutive or ingressive devices may be augmented by the larger capability of impactive methods once the required object surface is lifted some small distance above the level of the unwanted remainder. Additional problems are likely to surface should the objects be made from many different materials. A good example of this problem exists with most domestic and industrial waste, all of which require separation prior to recycling.

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

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The majority of commercially available robot grippers are intended for the handling of rigid three dimensional objects of predictable size and shape, such as metal castings, plastic mouldings etc. However, materials found in bulk waste may be rigid, semi-rigid or limp. The handling of non-rigid materials such as fabric, foam, sponge, polymer sheet etc. presents additional problems not easily addressable using conventional robot grippers. Many robot grippers originally designed for other applications, such as fabric and composite handling, are also applicable to the manipulation of many mixed products – including garbage.

Many suggestions for both the pre-sorting [10-3] and post-sorting [10-4] of domestic waste have been made in the past, some of which are now implemented. The former is normally carried out manually by the domestic user, the latter by machine with some manual assistance [10-4].

The selective recycling of mixed solid waste products relies on first identifying the material and then removing it from the whole. Current research suggests that the identification process can be achieved through the use of sensors [2-4] or combined with the gripping process by designing the robot endeffector so that prehension is possible only with a limited range of material types. Once identified, it is desirable to acquire and retain only the particular material surface required for sorting. Further sensory investigation can then be employed to determine the mix of materials present in the acquired object.

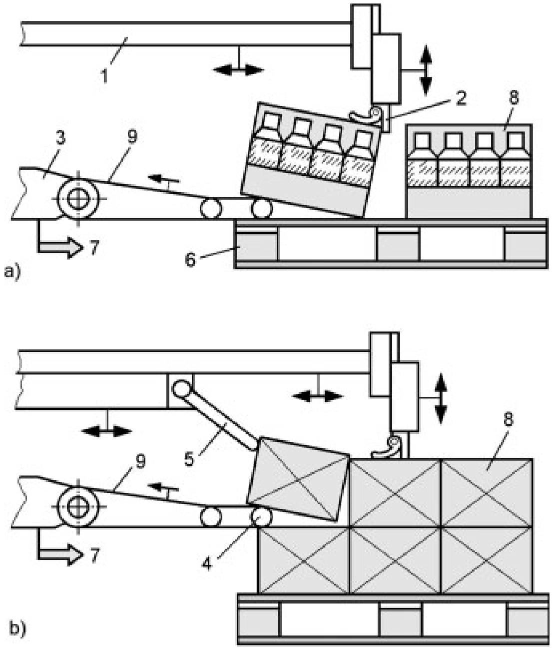
10.2 Separation of Rigid Three Dimensional Objects

Inelastic articles such as packages or bottle crates require additional equipment to ensure retention as illustrated by two examples in Figure 10.1. The object is held in place or slightly tilted to allow access from underneath by the conveyor. Prehension of the object is achieved by virtue of the large coefficient of friction on the conveyor belt surface. As a rule such systems require sensory integration for precise positional control.

10.3 Separation of Rigid Sheet Materials

10.3.1 Gripping of Thin Blanks from a Magazine

Separation of standard sized paper sheets is normally carried out automatically using high friction coefficient silicone rubber rollers as found in photocopiers and printers. Due to the low cost and availability of dedicated hardware such tasks are seldom carried out by robot. For thicker materials of varying size and low batch sizes a robotic solution can be appropriate. Carton blanks, instruction manuals, journals etc. must be separated from stacks of the like and automatically packaged. A typical example, where the objects are gripped and separated from the underside of the stack can be seen in Figure 10.2. In the first phase, the lowest object is prehended by vacuum suction and bent by 90°. In the sec-



1 countermovement retainer
2 locking element
3 roller gripper
4 high friction roller
5 anti-tilt support
6 transport pallet
7 gripper motion
8 prehended object
9 conveyor belt

Fig. 10.1: Roller gripper for non-flexible objects
a) removing bottle crates
b) removing packages

ond phase, the free end of the bent object is clamping between the jaws of an impactive gripper. Upon closing of the gripper jaws the vacuum to the first device is removed and the impactive gripper removes the object from the magazine. This two-stage (separation and prehension) process is expedient in that parts of both operations run parallel to on another.

One of the main problems associated with all astrictive methods for the handling of thin metal sheets is the separation of an individual object from a stack of the same. One effi-

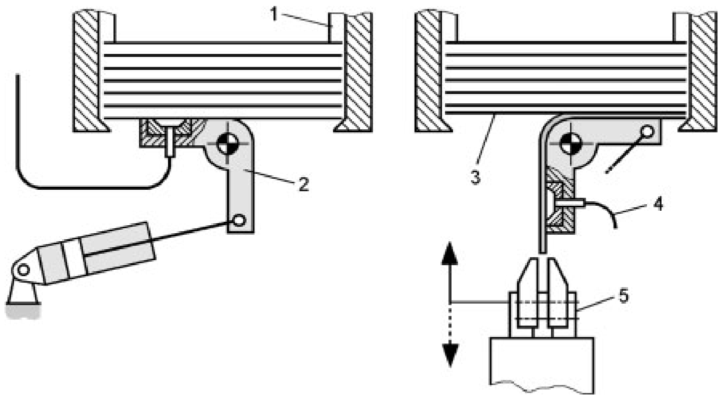


Fig. 10.2: Prehension of thin blanks from a stack magazine
1 magazine, 2 astrictive gripper, 3 blank stack, 4 vacuum supply, 5 impactive gripper

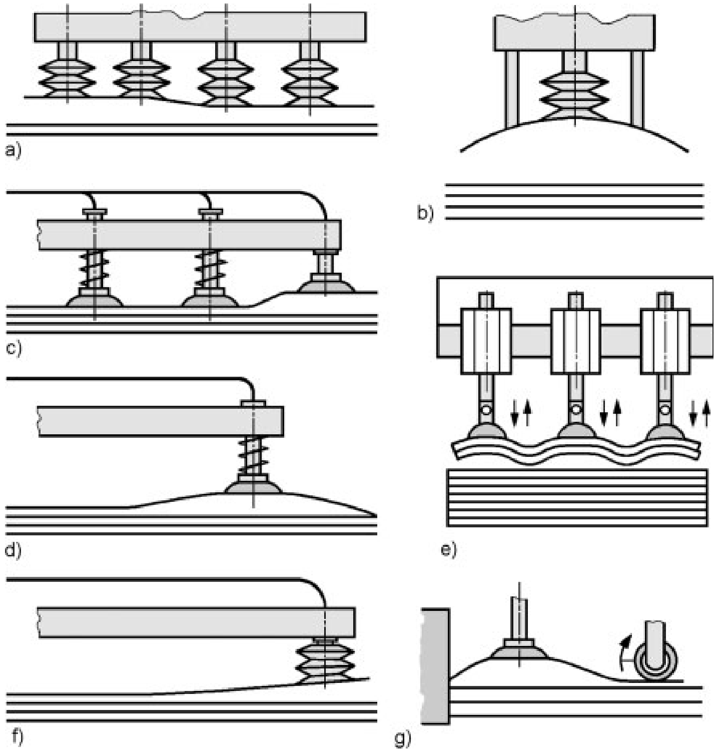


Fig. 10.3: Separation of metal sheets during vacuum prehension
a) variation of the vacuum pressure, b) suction against constraints, c) combination of stiff and sprung suction heads, d) prehension near object edges, e) deliberate cambering, f) prehension at outer edge, g) cambering prior to prehension

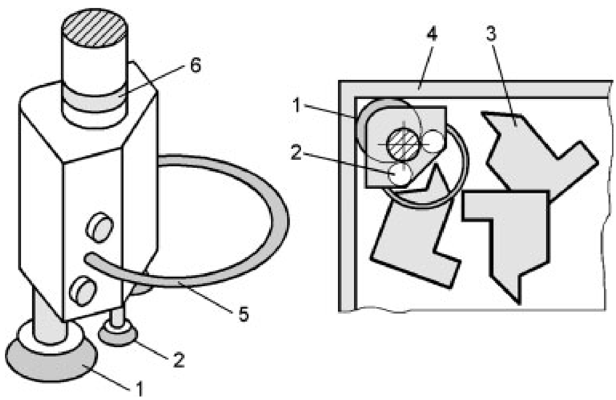


Fig. 10.4: Suction gripper for gripping in box corners (right: top view)
1 large suction cap, 2 small suction cap, 3 workpiece, 4 box or pallet, 5 hand grip for guidance, 6 swivel joint

cient method to avoid this is to camber the sheet so that adhering second, and subsequent, sheets are separated. This can be facilitated by appropriate design of the gripper. Some possibilities are shown in Figure 10.3.

The vacuum suction gripper depicted in Figure 10.4 is tailored to a different task. It possesses several suction disks which are arranged in such a way that the prehension of flat parts presented from the corners of a box or pallet is possible. The suction gripper is attached to a hand driven manipulator and is visually guided.

The smaller suction caps are activated after prehension by the larger suction cap and partial withdrawal of the endeffector. This ensures a stable retention of the object without the danger of acquiring an unwanted plurality of objects.

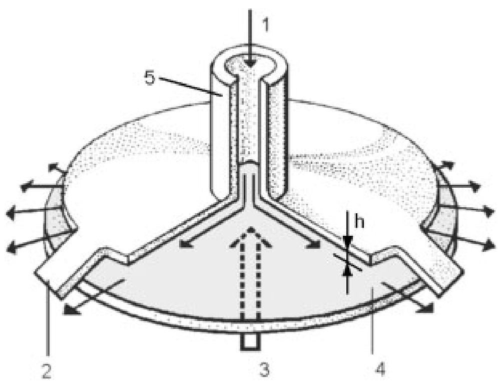
10.3.2
Air Flow Grippers

The blasting of an air jet close to a nozzle producing suction may appear as an aerodynamic paradox. However, the narrowing of the flow lines between the component and the gripper results in an overpressure which lifts the workpiece on an air cushion beneath the gripper. This effect develops only if a counter plate is present in order to create a gap between the lifted object and the nozzle. Figure 10.5 shows an example of an air flow gripper (sometimes called a *Bernoulli* lift unit) suitable for the prehension, and separation, of semiconductor wafers [10-5] for which the above conditions are fulfilled.

The underlying physical principle can be explained with the help of the *Bernoulli* equation. For a closed pneumatic system:

$$\varrho \frac{v_1^2}{2} + p_\mathrm{n} = 2 \cdot \varrho \frac{v_2^2}{2} + p_\mathrm{g} \tag{10.1}$$

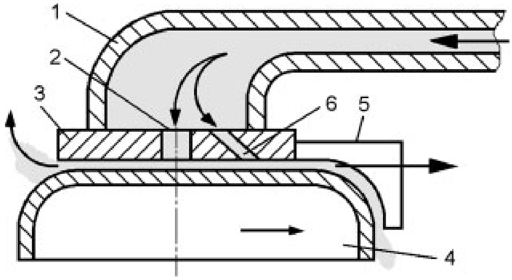
v_1 air flow velocity in the nozzle
v_2 air flow velocity in the gap
p_n pressure in the nozzle
p_g pressure in the gap
ϱ air density



1 compressed air
2 centring element
3 holding force
4 workpiece
5 nozzle

h gap height

Fig. 10.5: Air flow gripper



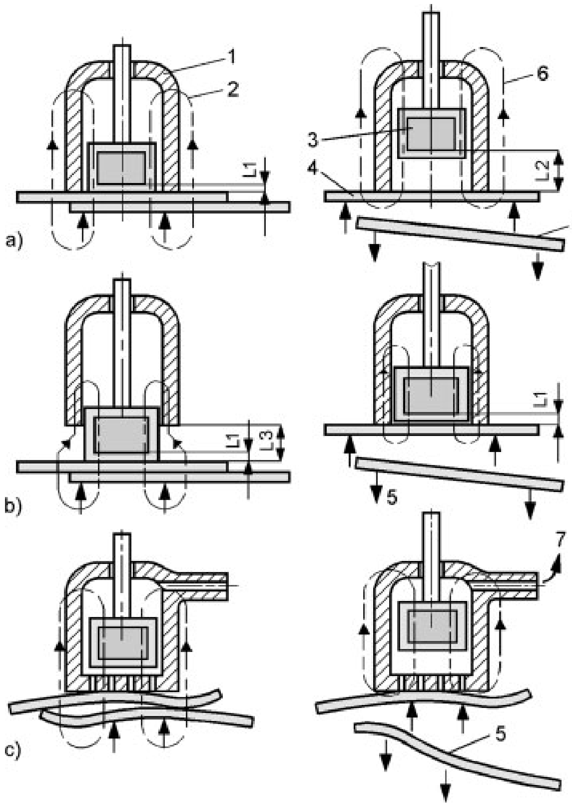
1 air channel
2 nozzle
3 nozzle plate
4 workpiece
5 stop
6 inclined flow nozzle

Fig. 10.6: Air flow gripper nozzle alignment

The analytical relationship for the pressure in the gap can be obtained from equation (10.1), assuming mass continuity:

$$p_g = p_n + \frac{m^2}{2 \cdot b^2 \cdot \varrho} \left(\frac{1}{d^2} - \frac{1}{2 \cdot h^2} \right) \qquad (10.2)$$

m mass
b nozzle width
h gap height
d nozzle diameter



1 housing
2 magnetic flux lines
3 permanent magnet
4 workpiece
5 effects of separation
6 displacement of field lines
7 air suction

L_i air gap

Fig. 10.7: Permanent magnet gripper
a) field line displacement for non-ferromagnetic housing
b) field line displacement for ferromagnetic housing
c) combination of a permanent magnet and vacuum

If the pressure in the gap drops below the surrounding atmospheric pressure the resulting astriction force holds the object in the vicinity of the nozzle plate. This allows the prehension of thin (light) sensitive parts. The same principle is used for the prehension of large paper or foil parts. Air flow must be maintained during the whole handling procedure. Modifications to this basic design also exist. Figure 10.6 shows an air flow gripper which is equipped with an additional inclined flow nozzle. This nozzle produces a small force impulse in the direction of the stop causing alignment of the object relative to the nozzle plate and thus is defining its position

Unlike electroadhesion, the forces due to magnetoadhesion are not limited to an interface between two surfaces. Magnetic fields tend to permeate deeply into a magnetic medium, whether the medium is mechanically homogeneous or not. The permanent magnet gripper for thin metal sheets shown in Figure 10.7 is designed for different operational modes. The main object is separation of the uppermost sheet from stacks of the same.

In Figure 10.7 a the magnet is applied to the sheet metal stack. Lifting of the magnet against the nonmagnetic (aluminium or brass) housing then reduces the magnetic field to a threshold whereby only one sheet can remain adhered. If the housing is ferromagnetic then the magnetic flux lines will follow this path as shown in Figure 10.7 b.

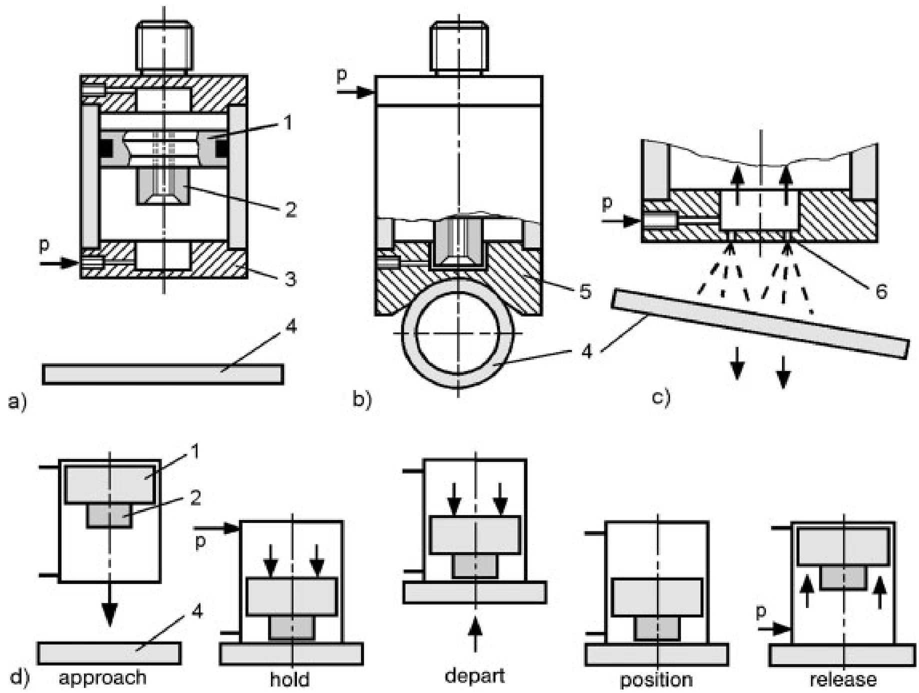
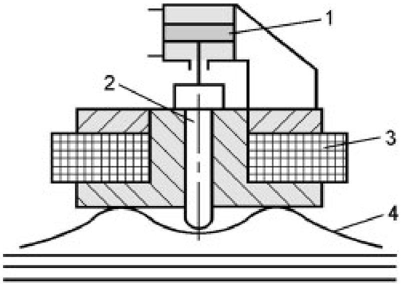


Fig. 10.8: Permanent magnet gripper with relocatable magnetic field
a) sectional view of a magnetic gripper, b) cylinder base as a form retainer, c) pneumatically assisted release, d) handling sequence
1 piston, 2 permanent magnet, 3 brass cap, 4 workpiece, 5 cast brass head, 6 brass nozzle plate, *p* compressed air supply



1 short stroke cylinder
2 pressure pin
3 magnet
4 sheet metal stack

Fig. 10.9: Magnetoadhesor with ejection pin

An interesting combination consists of magnetic fields and vacuum as shown in Figure 10.7 c. The magnet is moved downwards and simultaneously the vacuum is switched on. On prehension the magnet is moved upwards leaving only one sheet held by the remaining vacuum force whilst other sheets, devoid of magnetic retention force, fall away.

In order to avoid direct contact between workpiece and magnet, the magnetic field can be displaced as already suggested in Figure 10.7. For the permanent magnet gripper shown in Figure 10.8 this can be realized electrically or pneumatically. In the first phase, as the magnet is moved downwards to a position just over the object, the magnetic field is not active. The magnetic field is then activated to achieve prehension. On release, the magnet is simply pulled against the collar. The cylinder base may also be equipped with blow nozzles to assist release.

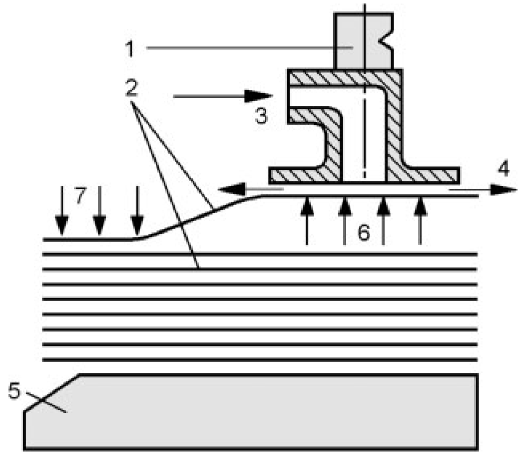
This design also overcomes problems with remanence because a direct contact with the object is avoided (there is always a very small air gap).

An interesting application is the prehension of iron, stainless steel and aluminium sheets without exchanging the gripper. In the case of steel sheets the vacuum and magnetic forces are added together while for the lighter aluminium sheets only the vacuum is effective. When releasing the iron sheets the magnetic force holds the object until a blow-off valve creates an underpressure. If the magnet is now switched off, the object is ejected within a very short time. This allows companies working with sheet metals to grasp 90 to 95 % of all sheet metal types without retooling (*Goudsmit-Magnetics*).

Another solution can be seen in Figure 10.9. The pin presses against the uppermost metal sheet and slightly curves it so that adhering sheets are ejected. Of course there are some drawbacks related to the necessity of having two sources of energy and their respective control.

10.4 Separation of Non-Rigid Sheet Materials

Another, albeit very difficult field of application, is the prehension and separation of air permeable textile material panels from a stack. One such gripper head is shown in Figure 10.10. Success depends on the extent of the porosity, whether further parts can adhere mechanically (hairiness), the size of the material panels and their thickness, the air properties (density, pressure and velocity), the geometrical dimensions of the stack and other factors.



1 gripping head
2 textile panels
3 compressed air supply
4 escaping air
5 air impermeable table
6 underpressure region
7 region of atmospheric pressure

Fig. 10.10: Separating of porous textile panels

Calculation of the relevant parameters is not simple. In [10-6] the breaking down into the partial systems of "mass flow" and "filter stream" are recommended.

Though some progress in laser cutting has been made in recent years [10-7], until and unless single layer cloth cutting becomes practical and economical, fabric will continue to be die or knife cut from multiple layers. Consequently the most important task in any form of automated textile fabric handling is the removal of a single ply from a stack of the same. Without the ability to perform this basic task quickly and efficiently no totally automated system can function successfully as all subsequent operations depend on the accomplishment of this initial task. After a single ply has been removed from such a stack it must be positioned and orientated ready for the next operation.

Despite the extensive variety of non-rigid materials commonly used, there are two distinctly different forms of inter-panel adhesion found with most textiles and fibrous materials. In the case of woven fabrics, the die cutting process causes the linting (entanglement of loose strands) at the freshly cut edges of the fabric, and hence provides the layers of material with the ability to cling together. In the case of knitted fabrics which are capable of considerably greater stretch than woven materials, the forces of inter-panel adhesion exist across the entire surface area. Though the die cutting process tends less with knitted fabrics to enhance adhesion at the edges by linting, it does stretch the layers at differing rates of strain thus enhancing the ability of the small hairs to intertwine over the entire surface interface. In addition to these basic differences, every type of fabric has its own unique properties which are highly dependant on the type of yarn used. In fact, two panels cut from different areas on the same roll of cloth can exhibit noticeably different characteristics [6-15]. Due to the close similarity in flocculence over the surface, most fibrous composite materials tend to behave more like knitted than woven fabrics.

The actions of prehension and separation may be considered as discrete or simultaneous actions [10-8]. In most practical circumstances, in addition to the basic prehension device, an additional means is required to ensure ply separation. This may be in the form of pneumatic assistance [4-1], secondary mechanical help [10-9] or by deliberately designing the gripper to exploit both cohesive and shear forces [5-29]. Whichever method of prehension is used and no matter how many panels are removed in a single acquisition operation, it is imperative that the top of the stack remains flat and undisturbed so that the next gripping operation may begin with an expected state. If this is not the case and the uppermost panel is left badly creased or folded then the next, and subsequent, acquisition attempts are likely to fail.

Due to fraying, most panel edges cannot easily be measured to an accuracy of better than $\pm$ 1 mm. However, contrary to expectations, this does not simply mean a position accuracy of $\pm$ 1 mm is adequate. It is not only position accuracy which is important but also path accuracy. It is no good trying to use a cylindrical gripping device with a robot having a positional accuracy of $\pm$ 1 mm when its path accuracy is $\pm$ 5 mm. The use of cylindrical grippers requires precise maintenance of height and path trajectory during the acquisition process. For this reason alone, ply separation tests carried out with robot gripping heads by hand are totally meaningless.

In fact, as soon as initial prehension has been achieved, the remainder of the separation process relies very heavily on the agility of the robot. It was a common mistake during the 1990s to use much cheaper, lower accuracy robots for textile handling in order to fit in with the industries cost desires rather than engineering requirements. Such projects are almost certainly doomed to failure where ply separation is concerned.

Figure 10.11 shows the schematic diagram of a ply separation method, achieved by applying a bending force to the uppermost ply using a planar gripping head. To prevent rotation of the gripper into the stack the tool centre T must be offset by half the diameter of the gripping head. Alternatively, a compound transformation consisting of a clockwise rotation and two simultaneous translations in x and y may be used. Either way this is not a problem when a high level robot programming language is used, but very difficult to implement on simple hard automation systems where each joint must be individually controlled.

$$P_1 = [-\ D\ 0\ 0 1]^{\mathrm{T}} \tag{10.3}$$

For a clockwise rotation of point P_0 the gripping surface can be rotated through an angle θ using the transformation (10.4):

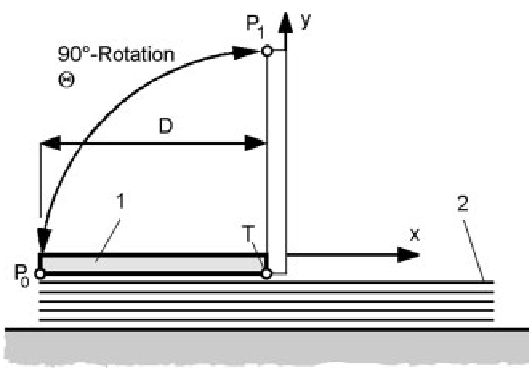


Fig. 10.11: Robot gripper employing bending action

$$P_1 = \begin{bmatrix} \cos\Theta & \sin\Theta & 0 & 0 \\ -\sin\Theta & \cos\Theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} -D \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{10.4}$$

$P_1 =$ for an angle $\Theta = \pi/2$ radians (90°)

$$P_1 = [0 \ D \ 0 \ 1]^T \tag{10.5}$$

Assuming the robot is capable, this simple scenario allows for the incorporation of additional small translations and rotations in all three axes in order to exploit the stretch properties of many knitted fabrics.

10.4.1 Roller Grippers

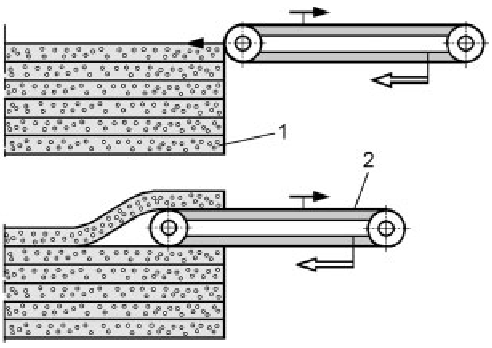
The separation of materials, particularly those which cling together, can be greatly assisted by integrating the prehension medium with a cylindrical surface. By this means plies of material can be separated from one another effectively by peeling the top layer free from the stack below (as expressed in the rotational kinematic matrix 10.4). Many prehension techniques are suitable for such adaptation and for further part feeding purposes the system may be expanded to include belt systems.

The rolling prehension principle is based on the slack-free transportation of the acquired goods [10-10]. The gripper makes contact with the object frontally through a rotating roller or a revolving belt. In the case of ingressive prehension techniques the roller may simply be a hackle. Alternatively, a belt covered with small needles or wire points may be used. For the removal of smooth surfaced materials such as paper or polymer sheet, high friction silicone rubber may be employed. As a result of the ingressive or contiguitive coupling the object is lifted onto the gripper surface with subsequent motion of the belt, as shown in Figure 10.12 leading to object removal.

The gripper shown in Figure 10.13 first makes contact with the stack through a retaining rail. The uppermost ply is then rolled towards the retaining rail by motor driven rota-

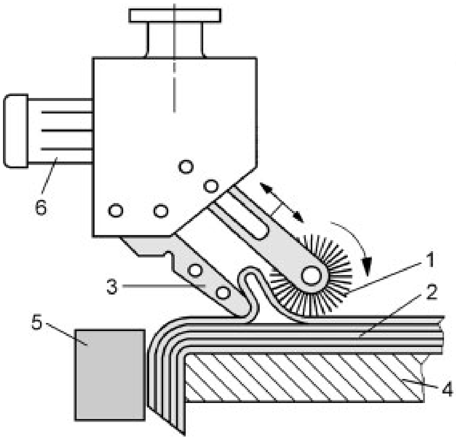
a)

b)



1 stack of plies to be removed
2 ingressive or contigutive belt

Fig. 10.12: Principle of the roller gripper
a) initiation of prehension
b) transport and retention



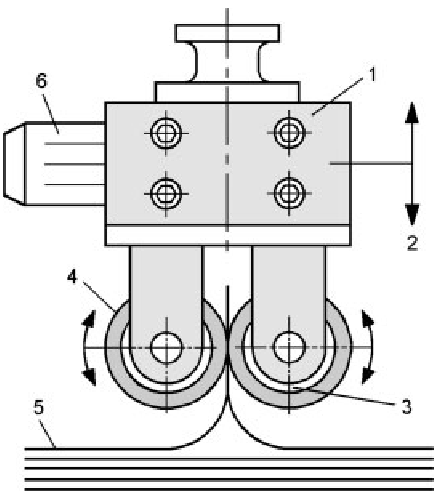
1 cylindrical hackle or brush
2 stack
3 retaining rail
4 table surface
5 stop constraint
6 motor

Fig. 10.13: Gripper for textile materials [10-11]

tion of the hackle or cylindrical brush. This ply may now be lifted clear of the stack. In addition to simple vertical movement of the robot, some horizontal translation will almost certainly be necessary in order to avoid distortion of the next layer during removal of the first.

Two knurled rollers or hackles, rotated against one another can also be used to lift sheet materials. A less intrusive variation, originally considered for the handling of small leather and composite parts [10-12], relies on the frictional forces of silicone rubber rollers (as used in photo copiers for paper feeding). Rotation initiates prehension and continues until the surface of the material lies between the rollers. The motor then holds the rollers fixed in this position thus maintaining retention impactively (Fig. 10.14).

The silicone rubber rollers combine the attributes of a very high frictional coefficient with a soft compliant physical nature. Figure 10.15 shows the relation between grip width *W* to roller angle a for a given roller radius *R*.



1 gripper housing
2 approaching motion
3 gripping roller
4 rubber coating
5 foil stack
6 stepping motor

Fig. 10.14: Roller gripper for polymer foil

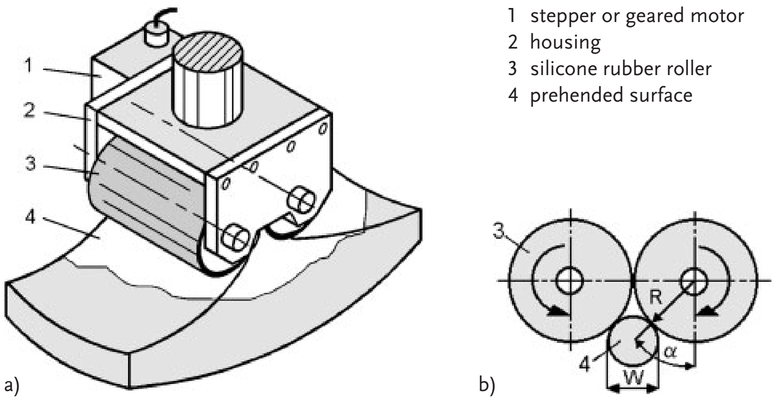


Fig. 10.15: Roller gripper with pinch effect
a) application example, b) gripping geometry

$$W = 2 \cdot R(1 - \sin \alpha) \tag{10.6}$$

The rotational force F_r is roughly equal to the vector sum of the lift force F_1 and the pinch force (that which tends to squeeze together the two parts of the surface in contact with the rollers) F_P as given by equation 10.7.

$$\vec{F}_r = \vec{F}_1 + \vec{F}_P \tag{10.7}$$

The following equations hold for the corresponding force components:

$$F_P = \mu \cdot F_r \cdot \cos \alpha \tag{10.8}$$

and

$$F_1 = \mu \cdot F_r \cdot \sin \alpha - m \cdot g \tag{10.9}$$

For silicone based elastomers, the coefficient of friction μ between the roller and the object upper surface can be assumed to be almost equal to 1. Lifting of the object by the robot requires that the factor $\mu \cdot F_r$ is significantly larger than $m \cdot g$ (m = object mass). The necessary rotational force F_r can be calculated from (10.8), (10.9) and (10.10) as follows:

$$\mathrm{F}_r = \sqrt{F_P + F_1} \tag{10.10}$$

Another application for this type of gripper is the handling of loosely bagged parts. During the initial prehension operation, the mass of the bag contents will not be relevant as only the bag surface is in contact with the rollers. Consequently, the mass and gravity parameters in formula (10.9) may be neglected until such a time as the endeffector and load are lifted from rest. At this point, provided F_r is large enough (due to securing of the rollers

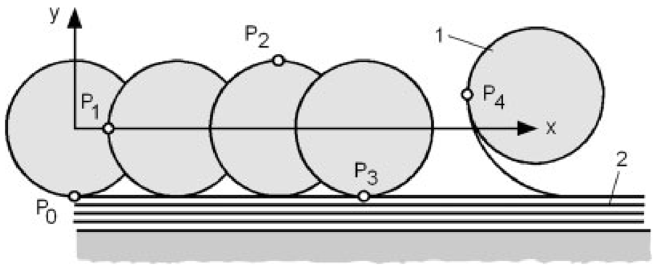


Fig. 10.16: Robot gripper exploiting rolling action

against rotation), continued prehension will be dependant only on μ. For practical purposes the coefficient of friction of the particular silicone rubber used in the manufacture of the rollers in contact with most polymer materials will be greater than 0.9. This compares with a steel on steel frictional coefficient which has a maximum of about 0.6 [10-13].

Figure 10.16 shows the schematic of a ply separation action when a cylindrical gripping head, whose tool centre T passes through the cylinders major axis centrum, is used.

For a free rolling gripping head all the manipulator need do is perform a simple linear translation along the x axis. Of course, there must be no movement in either the y or the z directions. This is almost impossible to achieve by hand but is perfectly routine for an industrial robot.

For a clockwise rotation, the gripping point P_0 will be moved to P_1 by the compound transformation given in (10.11), where the angle of rotation is again in radians.

$$P_1 = \begin{bmatrix} \cos\Theta & \sin\Theta & 0 & \pi \cdot r/2 \\ -\sin\Theta & \cos\Theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} -D \\ -r \\ 0 \\ 1 \end{bmatrix} \tag{10.11}$$

when $\Theta = \dfrac{\pi}{2}$

$$P_1 = \left[\frac{\pi \cdot r}{2} - r\ 0\ 0\ 1 \right]^{\mathrm{T}} \tag{10.12}$$

the direction of the new x axis shows that only shear forces are exploited

when $\Theta = \pi$

$$P_2 = [\pi \cdot r\ r\ 0\ 1]^{\mathrm{T}} \tag{10.13}$$

Now there exists a vertical shear and cohesive components

when $\Theta = 0$ or $\theta = 2\,\pi$

$$P_3 = [2 \cdot \pi \cdot r - r\ 0\ 1]^{\mathrm{T}} \tag{10.14}$$

A translation in the x axis by 2 π r causes a complete rotation and hence the y component of P_3 is equal to that of P_0. As long as the gripping cylinder is prevented from further rotation, the forces of prehension are now augmented by the frictional characteristics of the cloth against itself. This means that large and heavy fabric panels, which would otherwise suffer damage due to localised gripping stresses with ingressive methods, may now be lifted safely [10-14].

In all practical ply separation systems, energy must be supplied in order to break the forces of linting and inter-ply cohesion. As energy is proportional to the square of the velocity and directly related to the acceleration over a given distance, these become important factors. Consequently, a robot capable of high, and more importantly controllable, speed has significant advantages over single or low speed manipulators. An example of such an implementation on an *Adept* SCARA Robot [10-15] is shown in Figure 10.17 where a cylindrical electroadhesive gripper is used to separate one layer of polyester-cotton from a stack.

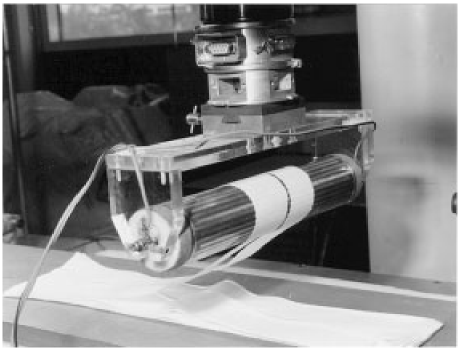
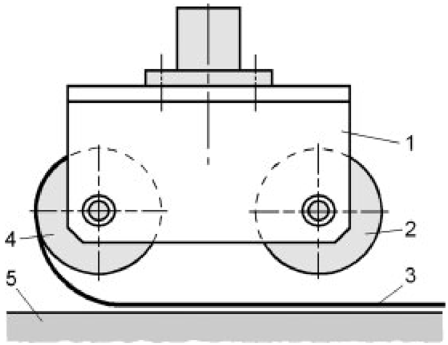


Fig. 10.17: Ply separation using a cylindrical electrostatic roller gripper.
(Photo: courtesy Brynmoor-Jones Library, University of Hull)

Unfortunately, this form of ply separation is limited to sheet materials having a degree of spring coefficient, i.e., woven or fibrous fabrics, metal and polymer film etc. Knitted fabrics, on the other hand, are completely limp and therefore usually require a different form of mechanical action (see Figure 6.3 in Chapter 6).

Previously it was stated that exact positioning of the panel is best done after the pick and place operation. This is not only true for cylindrical gripping heads where the panel must be rolled on and off thus increasing the likelihood of additional placement errors. With any form of prehension it is difficult to locate the exact position of an object whilst it is on the gripper and then to guarantee positional integrity throughout transportation and release [6-14]. The system invented by Kemp [10-9] achieved this on one edge of the fabric immediately after prehension, but was not capable of guaranteeing complete orientation and alignment after release.

In view of the problems associated with determining the precise position of the object whilst it is under prehension, a panel must be released from a gripper before it can be accurately and correctly orientated relative to some fixed datum point. This can be done, in conjunction with suitable sensors, by conveyor belt, air floatation [10-16] or vibratory table



1 housing
2 non-adhesive roller
3 fabric panel to be deposited
4 adhesive coated roller
5 work surface

Fig. 10.18: Contigutive cylinder and removal mechanism

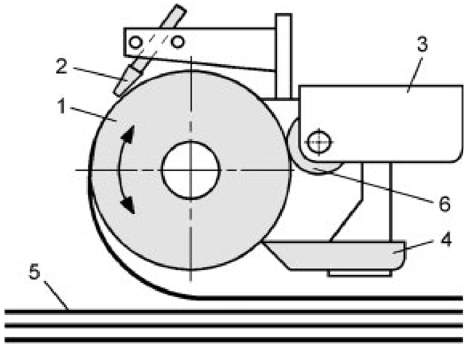
[10-17]. Final positioning is controlled by physical constraining walls at the sides of the table. An additional advantage of these orientation techniques is that any rucks or ripples in the fabric tend to settle out during linear vibratory motion.

Where ply separation of fabric panels from stacks of freshly cut material are concerned, the gripping mechanism may also be required to perform some action to break the forces of cohesion between the plies due to flocculent coagulation, linting at the edges etc. The roller action, illustrated used in conjunction with astrictive gripping methods mentioned previously [5-29] can also be implemented with a tacky surface. Object removal cannot be achieved by simply removing the supply and rolling the panel free, as is the case with astrictive techniques. The adhesive effect cannot be externally controlled so some form of mechanical force is required to peel the fabric panel from the cylinder. Figure 10.18 shows a typical example of a suitable configuration.

A combination of two rollers, one adhesive coated the other not, offset from on another as shown in Figure 10.18, permits simple removal of a panel. To acquire the panel, the adhesive coated cylinder is rolled over the fabric panel in order to achieve prehension, the non-adhesive roller simply playing a passive roll. To eject the panel, it must be rolled free but here the auxiliary, non-adhesive coated cylinder is used to trap the panel against the surface it is being deposited onto (e.g. table top) so as to force it to peel away from the adhesive roller as it passes over the surface.

With woven, and other fabrics having a degree of spring, the rolling action tends to break the linting forces and the fabrics natural spring causes excess plies to flip back onto the stack. For much limper knitted materials, an air jet (or brush) mechanism as shown in Figure 10.19 or the non-adhesive roller can be used to assist the removal of unwanted plies. Due to the roller being capable of trapping the end of a cloth against itself after one complete rotation, an adhesive having a short holding time is permissible.

After a large number of pick and place operations, dust trapped between fabric panels, loose threads and lint tend to gather on the adhesive surface. These can easily be removed by passing the gripper over a water or solvent soaked pad, depending on the type of permatack adhesive used. The ability of such adhesives to remain operative when wet, allows normal operation to recommence instantly with very little time loss. If used with a water de-activated adhesive then some means of rapid drying must be provided. Experiments with vinyl based adhesives have shown that a rotating sponge material moistened in warm



1 adhesive coated cylinder
2 pneumatic or mechanical ejector
3 cleaning water tank
4 dust catchment
5 fabric stack
6 rotating foam cleaning pad

Fig. 10.19: Contigutive gripper with integrated cleaning

water provides the quickest method, both in terms of contamination removal and drying (a typical cleaning cycle time of less than 3 seconds may be expected). Drying is further augmented by contact with the next panel to be lifted [6-7]. Where cylindrical gripping heads are used cleaning can be carried out on a continuous basis with the surface of the adhesive roller being made to rub against a moistened pad as in Figure 10.19.

11
Instrumentation and Control

Few, if any, modern robotic systems operate without additional sensors for object detection, guidance and control. Furthermore, the control of external devices, including grippers, is usually carried out directly from the robot controller. This chapter deals with those aspects of instrumentation and control directly relevant to prehension operations.

11.1
Gripper Sensor Technology

Sensory integration of robot grippers cannot easily be modelled on the human hand since exact reproduction would be virtually impossible and would make little sense from an industrial point of view. The hand possesses many specialized receptors. These are:
- **Fingertips:** contains about 140 *Meissner corpuscles* per cm^2 which are sensitive to small changes in pressure.
- **Vater-Pacini lamellary corpuscles:** react to acceleration of pressure stimuli.
- **Skin upper surface:** *Merkel tactile cells* react to pressure and deformation.
- **Hand inner surface:** about 17 000 *Ruffini corpuscles* react to straining of the skin.

Moreover, there exist a lot of "free" nerve endings which also fulfil sensory tasks like detection of heat or cold. Hair follicle receptors represent additional multipurpose feelers. However, almost all "nerve sensors" are logarithmic and react only to parameter variations. There is considerable crosstalk among the sensor elements, thus human "sensors" are of very limited use for exact measurement purposes.

In handling technology, only very simple prehension tasks can be performed without the assistance of sensors. The most significant function is finger position control.

11.2
Perception Types

There are three types of perception which are related to gripper technology:
- Proximity or presence detection of objects to be prehended on approach without registration of geometrical details.

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- Verification of prehension or release (see Section 11.2.4 and particularly Figure 11.23).
- Perception of object position and orientation. This is often connected with multidimensional monitoring of a scene or an object.

If the boundary situations are simple enough that constant grasp and release conditions can be ensured then the degree of sensory integration can be minimised. However, varying geometrical and temporal tolerances mean that this is rarely the case. There are three basic sensory programming strategies:

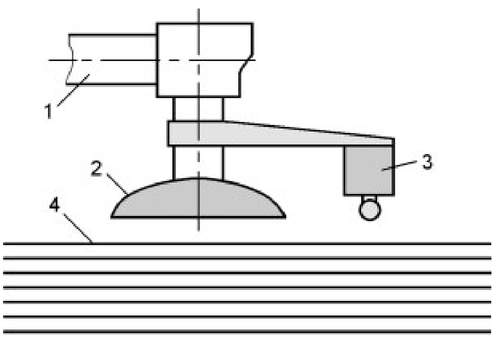
- Discrete sensing: interrogation of sensors at fixed points in a program.
- Sensory driven programming: program subroutines are called depending on sensor outputs at fixed program points.
- Sensory transition driven programming: program subroutines are called (often using software interrupts) depending on changes in sensor outputs.

However, the type of sensor required is largely independent of the chosen programming strategy and the rest of this chapter will deal with a selection of the most commonly used sensors relevant to the task of prehension. More extensive details can be found in [11-1].

11.2.1
Tactile Sensors

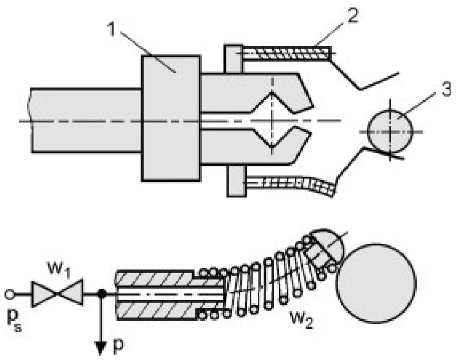
Tactile sensors react to physical contact. If a contact is established the corresponding information is sent to the control unit in order, e.g., to terminate the movement of the arm of the handling equipment. In the simplest case it is sufficient to have a binary sensor. Binary sensors simply register thresholds for a given signal, e.g. contact between the suction head and an object surface. As a consequence of this sensor value change, the vacuum is switched on in order to activate prehension. This principle is presented in Figure 11.1. The exact position of the sensor may be lowered in order to provide an approach warning just before the suction head reaches the object.

Alternatively such sensors can also be directly integrated into the suction head or can take the form of air leakage detectors thus indicating an inadequate seal between suction cup and object surface.



1 robot arm
2 vacuum suction cup
3 binary sensor
4 plate stack

Fig. 11.1: Vacuum suction cup with binary sensor



1 gripper
2 tactile feeler (tightly wound, air-tight spring)
3 workpiece

W_1 fixed (preset) pneumatic resistance
W_2 variable pneumatic resistance
p measured pressure
p_s feed pressure

Fig. 11.2: Pneumatic tactile feelers attached to gripper jaws

In a similar manner, the "palpation" of an object can also be realized pneumatically. Figure 11.2 shows tactile feelers which are attached to the gripper jaws. The feelers consist of tightly wound springs which release air if deflected thus resulting in measurable internal pressure changes.

There are many forms of tactile sensor and their respective array configurations. The commonest forms are piezoresistive, capacitive and optical (whether infra-red or visible light). Since the advent of finger print recognition systems their price has dropped dramatically. The basic principle of a tactile array, integrated with a gripper finger is shown in Figure 11.3. It is possible to build the sensor arrays small enough to be used in applications like minimally invasive surgery.

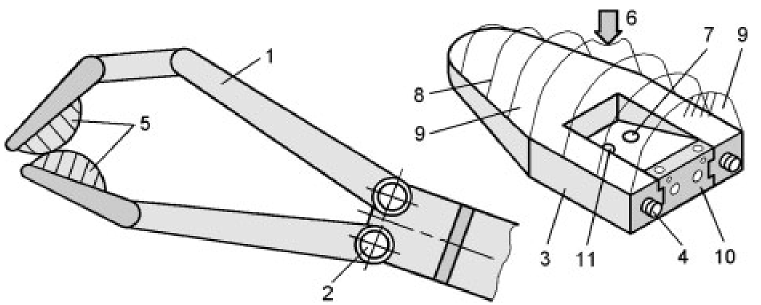


Fig. 11.3: Two-finger hand with sensory fingertips (after an idea of *Geisen*)
1 finger, 2 joint, 3 fingertip base, 4 coupling element, 5 fingertips, 6 tactile event, 7 camera lens, 8 line sensor, 9 flexible membrane, 10 CCD camera, 11 illumination

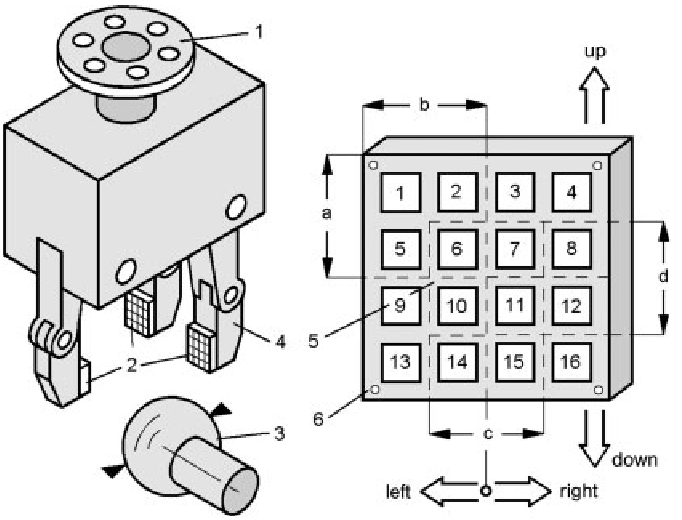
The following table [11-2] contains information about a selection of standard tactile arrays.

Contact with the object produces a digital imprint which can be transformed with the corresponding software into information about the contour characteristics, dimensions, position, and possibly orientation. The better the resolution of the tactile array, the finer the object feature identification.

Parameter	Supplier of tactile sensor arrays			
	Siemens	**Veridicom**	**Harris**	**Thomson-CSF**
Principle	Capacitive	Capacitive	Capacitive	Optical
Sensor range	13×13 mm	15×15 mm	14×14 mm	2×17.5 mm
Pixel number	256×256	300×300	144×144	40×350
Resolution	500 dpi	500 dpi	520 dpi	500 dpi
Supply voltage	5 V	3.3 V	5 V	5 V
Power consumption	approx. 30 mW	$<$ 100 mW	–	280 mW
Response time	$<$ 0.5 s	$<$ 1 s	$<$ 2 s	approx. 1 s
Data format	Bitmap	TIF	Bitmap	Bitmap

A gripper endowed with tactile sensor arrays at the fingertips is shown in Figure 11.4. The centre of the gripper jaw is represented by the sensor elements 6–7 to 10–11. If prehension is inaccurate this will be detected by the sensitive elements at the edge, resulting in a control signal. This will, in turn, direct the robot to repeat the gripping procedure with a new position.

In addition to 6-axes of force-moment sensing in each fingertip, the GIFU five-finger hand [11-4] refered to in Chapter 8, is equipped with a tactile sensor foil on the inner side of the fingers. The sensor foil consists of 624 tactile elements, the so-called taxels, 312 of which are in the palm, 72 in the thumb and 60 in each of the fingers. See Chapter 8 for more details on dextrous hands.

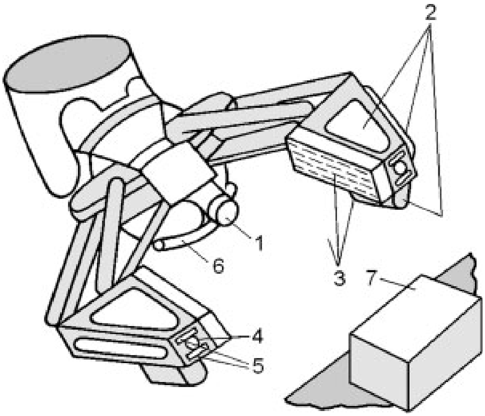


1 connection flange
2 4×4 tactile matrix
3 object
4 finger
5 central sensors
6 sensor arrangement

Fig. 11.4: Robot gripper with 3 fingers equipped with tactile sensors [11-3]

11.2.2 Proximity Sensors

The first sensory integrated grippers were implemented by *H. Ernst* at MIT (USA) in 1960/61 based on the ideas of *M. Minski and C. Shannon* (1958). The problem to be solved was the automatic collection of cubes scattered on a surface. These first grippers, with what was then referred to as "artificial intelligence", are shown in Figure 11.5. Sensory integrated grippers are now widespread especially in complicated assembly tasks where objects of varying size, shape, mass, and material properties must be grasped and mounted within a single cycle.



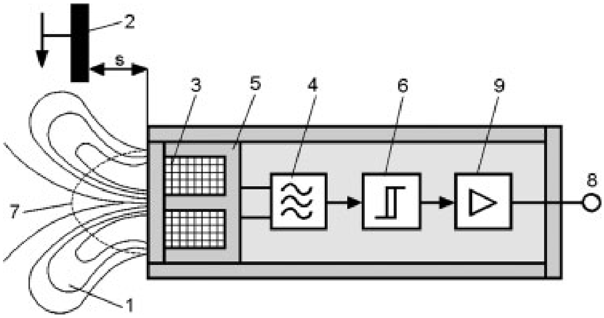
1 approach sensor
2 auxiliary tactile sensors
3 tactile sensor arrays
4 photodiode for approximate object detection
5 pressure sensor
6 contact (table surface) sensor
7 object

Fig. 11.5: Sensory integrated gripper after *Ernst* (MIT 1960/61)

> **Approach sensors** are non-contact sensors which deliver a signal from which information concerning the instantaneous distance to a given object can be derived. The signal coupling can be realized by inductive, capacitive, fluidic, optical or acoustic means.

Approach sensors can provide either a discrete binary output (proximity sensors) or an analogue measurement depending on the distance to the object to be detected. The basic principles used include:

- Inductive: suitable for electrically conducting objects. Can be usable up to several centimetres but recognition of some alloys and carbon fibre parts presents problems. Detection can also be dependant of the thickness of highly conducting objects.
- Capacitive: suitable for practically all materials with a few exceptions but limited to a few millimetres distance.
- Optically reflecting: applicable to optically reflecting objects and can be used over large distances. Highly dependant on object surface reflection properties.
- Optically transmission: applicable to opaque parts, not so suitable for some glasses and plastic parts.
- Acoustically reflecting: applicable to acoustically reflecting parts but not suitable for foamed plastics and some textile fibre products.



1 magnetic field lines
2 metal object (secondary)
3 oscillator coil (primary)
4 oscillator
5 ferrite core
6 *Schmitt* trigger
7 response limit (material dependant)
8 output signal
9 output amplifier

s separation (1 to 75 mm)

Fig. 11.6: Principle of the inductive proximity sensor

The principle of the inductive proximity sensors is shown in Figure 11.6. One can divide them into three functional blocks: oscillator, analyzing circuit and output stage. The basic principle is that of a transformer formed between the oscillator coil L_1 and resistance R_1 as the primary and the metal object which acts as the secondary winding with inductance L_2 and resistance R_2. The mutual inductance M_{12} ($M_{12} = M_{21}$) couple the two windings through the air gap s. The energy flowing into the object as a result of the high-frequency (usually about 10 kHz) alternating field ω, is what is effectively measured.

The primary and secondary voltages are defined by equations (11.1) and (11.2). Because the secondary is effectively short-circuited, V_2 must be zero.

$$V_1 = (R_1 + j\omega L_1)i_1 + j\omega M_{12}i_2 \tag{11.1}$$

$$V_2 = (R_2 + j\omega L_2)i_2 + j\omega M_{12}i_1 = 0 \tag{11.2}$$

Solving equation (11.2) for i_2 gives (11.3):

$$i_2 = \frac{-j\omega M_{12}i_1}{R_2 + j\omega L_2} \tag{11.3}$$

Setting i_2 into equation (11.1) and rationalising yields the transfer function (11.4)

$$\frac{V_1}{i_1} = R_1 + j\omega L_1 + (R_2 - j\omega L_2)\frac{\omega^2 M_{12}{}^2}{R_2{}^2 + \omega^2 L_2{}^2} \tag{11.4}$$

Splitting equation (11.4) into its real and imaginary components should convince the reader that changes in the objects electrical resistance R_2 alone will have a significant effect on the impedance "seen" by the oscillator which is why inductive proximity sensors are not restricted to use with ferrous materials alone.

Capacitive proximity sensors consist of two or more electrodes and an oscillator (around 100 kHz) behind a thin dielectric. The electrodes form a capacitor which partly determines the frequency of the oscillator. When an object (dielectric or conductor) approaches the sensor, the oscillator frequency changes as can be seen in Figure 11.7. The compensation

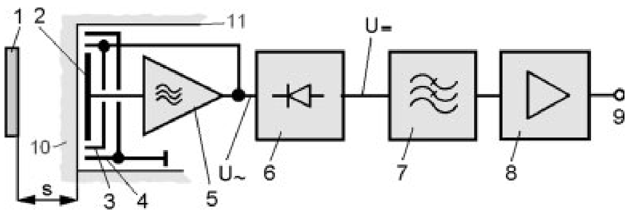
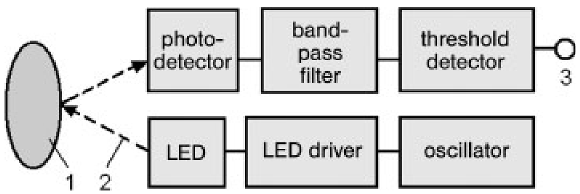


Fig. 11.7: Block diagram of a capacitive proximity sensor
1 object, 2 probe electrode, 3 compensation electrode, 4 screen, 5 oscillator, 6 rectifier, 7 filter, 8 output amplifier, 9 output signal, 10 accumulation of dirt, 11 housing

electrode serves to offset the accumulation of dirt and humidity condensation. Electrically conducting objects permit larger switching separations than insulating objects.

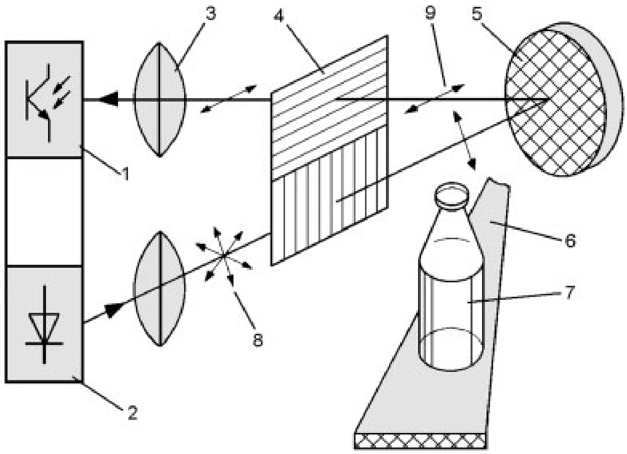
The commonest form of optical approach sensor is based on the reflection principle as shown in Figure 11.8. An LED or laser is modulated at a selected frequency (typically 10 kHz). Reflected light signals are received by the photodetector. The band-pass filter allows only signals of the same modulation frequency through, thereby eliminating signals from other sources (ambient light etc.).



1 object
2 light beam
3 output signal

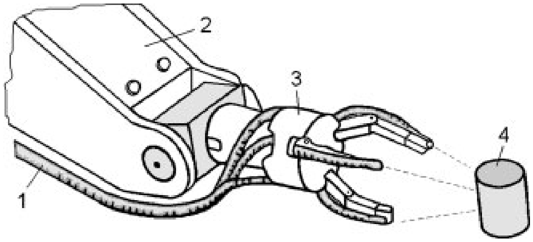
Fig. 11.8: Principle of the light reflection sensor

In some circumstances it is preferable to have a simple light interrupter, for example the detection of packages on a conveyor belt. However, highly reflective objects can cause problems. Polarized light whose polarization is rotated by 90° on reflection can be received by a detector sensitive only to orthogonally polarised light. This is achieved by the addition of a vertical (or horizontal) polarizer to the emitter and a horizontal (or vertical) polarizer



1 receiver
2 emitter
3 optics
4 polarization filters
5 retroreflector
6 conveyor belt
7 object
8 random light polarization
9 polarization plane, rotated by 90°

Fig. 11.9: Optical proximity detection using polarized light



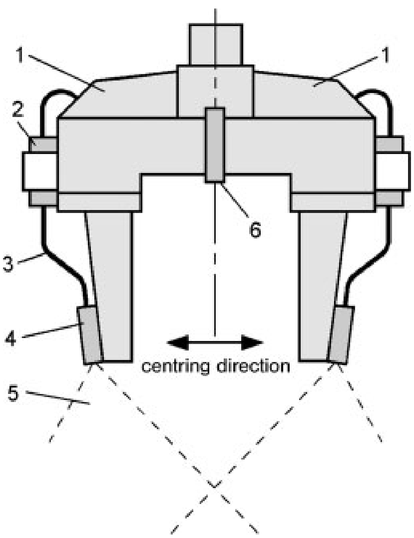
1 optical fibre
2 robot arm
3 three-finger gripper
4 workpiece

Fig. 11.10: Localization of the object with a reflection sensor

before the receiver. In addition to a mirror, the reflector contains a polarization rotator as shown in Figure 11.9.

Light for proximity detectors can also be directed with the help of optical fibres as shown in Figure 11.10. Though somewhat over dimensioned, the use of laser light and a CCD camera can give usable triangulation results.

In the same way it is possible to centre a two-jaw gripper with respect to an object. In the arrangement shown in Figure 11.11 this is achieved by comparing light intensities. Two reflected light proximity sensors with relatively large aperture angle are attached to the jaws. Centring with respect to the object is achieved by measuring and comparing light intensities.

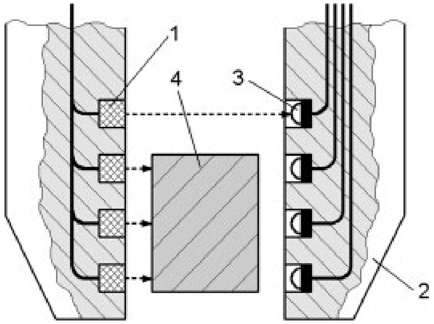


1 electronics
2 adjustment
3 optical fiber
4 sensor
5 monitor range
6 central sensor

Fig. 11.11: Gripper centring with reflected light sensors

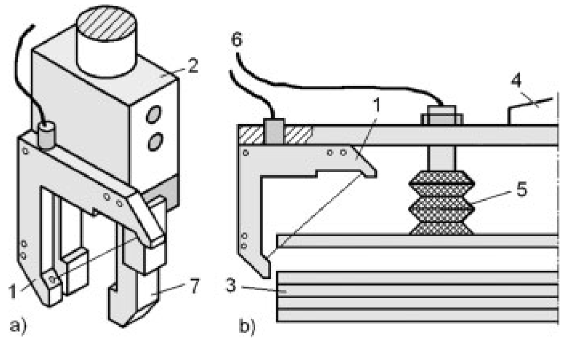
Figure 11.12 shows the arrangement of LED-photodiode pairs in the gripping surfaces of a parallel jaw gripper. Not only is object presence detection possible but given a large enough array information on the workpiece dimensions may be obtained. Synchronisation of the transmitter and receiver pairs in the respective arrays eliminates stray reflected light problems.

In addition to direct transmission of light between gripper fingers, diagonal light systems as depicted in Figure 11.13 have some advantages. A diagonal line of vision is es-



1 LED
2 gripper jaw
3 photodiode
4 gripped object

Fig. 11.12: Optical detection of objects between the gripper jaws



1 angle light barrier
2 gripper
3 plate stack
4 housing
5 suction bellows
6 connection lines
7 gripper jaw

Fig. 11.13: Detection of objects with a diagonal light barrier (*di-soric*).
Presence control for a) parallel jaw impactive gripper, b) astrictive vacuum gripper

pecially useful in handling techniques because the optical axis can be approached from all three spatial directions. In this arrangement it is possible to monitor exactly the approach of the stack upper layer and object presence can be continuously monitored by the sensor.

11.2.3
Measurement sensors

The exact distance to the object is an important parameter in any prehension procedure. This enables the robot controller to update target positions from within the program. Gripper jaw separation measurements can also be useful in determining object dimensions and ultimately identity. Distance measurement systems may also assist in guiding the gripper over obstacles. Integration of a CCD camera into the gripper is of course possible but this solution is rare in practice because the field of view is limited and easily obscured. A better solution is to mount the cameras some fixed distance from the target object.

A simpler and more commonly used method employs laser triangulation or acoustic sensors as shown in the block diagram of Figure 11.14.

Although electromagnetic transducers are used in larger systems, such as echo sounders in ships, most small scale acoustic systems employ piezoelectric transducers.

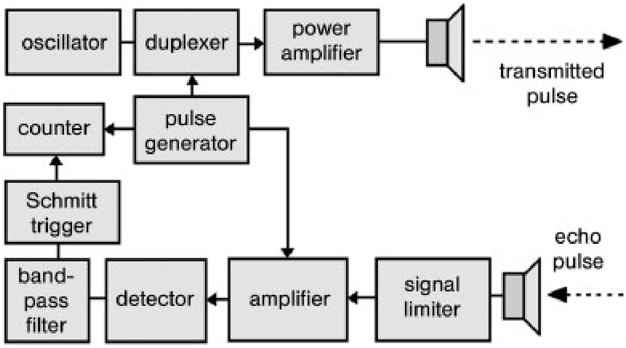


Fig. 11.14: Block diagram of an acoustic sensor (double-head system)

The ultrasound frequencies for such systems lie typically between 50 kHz and 250 kHz. Both single and double head systems are available. The detection range is limited by two factors: the distance between the transmitter and receiver transducers (zero for a single head system) and the recovery time between transmitted pulse and receivers readiness (minimal for a two head system). In a single head system, the received echo can only be recognized if its signal amplitude is larger than that of the decaying amplitude of the transmitter. That is why such a converter has a deadband within which no acoustic echo can be detected. For an object separation of 1 to 6 m the deadband can be as high as 0.5 m. The deadband can be considerably reduced by employing a double-head system as depicted in Figure 11.14. Unfortunately, the distance between the two heads results in a small shadow (usually about the same distance as the two heads are apart). Distance is calculated according to the echo return time as is illustrated in Figure 11.15.

The approximate spatial resolution, i.e. the smallest detectable separation change Δs, can be obtained from the following equation:

$$\Delta s = 2 \cdot \lambda = \frac{2 \cdot v}{f} \tag{11.5}$$

λ acoustic wavelength
f ultrasound carrier frequency

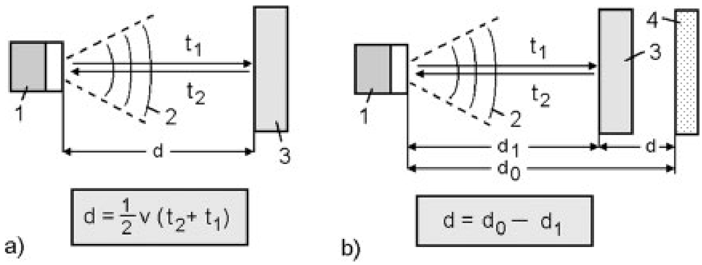
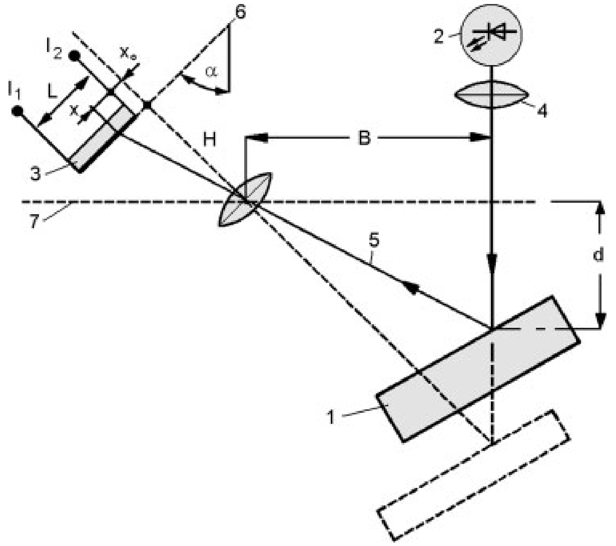


Fig. 11.15: Distance measurement with an ultrasonic sensor
a) pulse-echo method, b) relative difference measurement
1 sensor, 2 emitted pulse, 3 object, 4 reference object
d object separation, *t* acoustic wave transition time, *v* acoustic wave velocity

The propagation velocity of sound is temperature dependent and consequently many ultrasonic sensors have internal temperature compensation. The acoustic velocity in air increases by roughly 0.17% per °C. More advanced systems can also compensate for air pressure and humidity. Detailed treatment of ultrasonic technology can be found in [11-4].

The determination of distances by laser triangulation relies on the measurement of the angle of the reflected light beam from an objects surface. The trigonometrical principle is shown in detail in Figure 11.16. The distance *d* from the object can be derived from the deviation χ detected by the receiver. The following equation is valid for the geometry presented in Figure 11.16:

$$d = B \cdot \frac{H \cdot \tan\alpha - (\chi + \chi_0)}{H + (\chi + \chi_0) \cdot \tan\alpha} \tag{11.6}$$



1 object
2 light emitter
3 PSD receiver element
4 focusing lens
5 reflected measurement beam
6 image plane
7 reference plane

B base separation
d object separation
H image distance
x lateral deviation of the image point in the image plane

Fig. 11.16: Triangulation sensor geometry

In the given example an optical *position sensing detector* (PSD) serves as a receiver. Both digital (line scan cameras) and analogue (single light sensitive element) are available. In the latter case, differential measurement of the two photocurrents I_1 and I_2 determine the position x relative to some reference χ_0.

If the geometry is chosen in such a way that $\alpha = 90°$ and $\chi_0 = 0$ equation (11.6) yields:

$$d = H \cdot B \cdot \frac{1}{\chi} \tag{11.7}$$

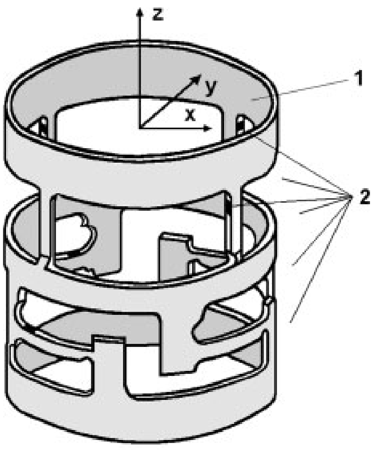
For the PSD receiver element used in (11.7) this gives:

$$d = \frac{H \cdot B \cdot (I_2 + I_1)}{L \cdot I_1} \tag{11.8}$$

Consequently, the separation d can be determined by differential measurement of the currents I_1 and I_2.

Force-torque measurement is an important element for the control and monitoring of automated assembly operations (the limiting of applied force in joining operations, overload control, collision detection). The relevant relationships have been studied in research laboratories since the mid 1980s [11-6] including the robot force adjustment in the case of "hard" contact with the environment [11-7].

Force-torque sensors are normally located between the gripper and the robot flange. These are deformable elements, for which there are many designs, one example of which is shown in Figure 11.17. The sensor allows the monitoring of three direct forces and three moments (torques). Sensitivity to force in a particular direction is achieved by mechanical decoupling built into the profiles of the rigid aluminium cylinder depicted in Figure 11.17. Strain gauge pairs attached to the back and front cylinder link surfaces provide differential strain measurements by changes in electrical resistance [11-8]. Both 3 beam and 4 beam (as in Figure 11.17) systems exist using either wire or silicon strain gauges.



1 deformation element, diameter: approx. 7 cm
2 strain gages

x, y, z sensor frame

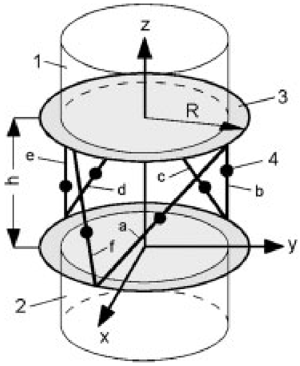
Fig. 11.17: Six-component force-torque sensor

As can be seen from Figure 11.18, the sensors monitor the compression and expansion of the rod links which are regarded as an elastic structure.

The matrix describes the relationships between the generalized forces and torques as a function of the actual measured forces F_a to F_f. The interested reader should consult [11-9] to [11-11] for a complete analysis.

Figure 11.19 shows another design of six-axis force-torque sensor which is capable of being integrated into a ball grip for man-machine interface purposes (right picture). The active part of the mechanics consists of two flange rings of different size for initiation of *actio* and *reactio*, and a connection block which interlinks the two flanges through 4 radial and 4 axial beams. The gripper is attached to the smaller ring (1).

There are 8 pairs of strain gages, the signals from which are transformed by the computer into force and moment values by vector multiplication with a 6×8 matrix ($6 = 3$ forces, 3 moments; $8 = 8$ measurement values). From this information the magnitude and



$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \frac{1}{2L} \begin{bmatrix} -R & 2R & -R & -R & 2R & -R \\ 2\sqrt{3}\cdot R & 0 & -2\sqrt{3}\cdot R & 2\sqrt{3}\cdot R & 0 & -2\sqrt{3}\cdot R \\ 2h & 2h & 2h & 2h & 2h & 2h \\ 0 & -\sqrt{3}\cdot h\cdot R & -\sqrt{3}\cdot h\cdot R & \sqrt{3}\cdot h\cdot R & \sqrt{3}\cdot h\cdot R & 0 \\ 2hR & -hR & -hR & -hR & -hR & 2hR \\ -\sqrt{3}\cdot R^2 & \sqrt{3}\cdot R^2 & -\sqrt{3}\cdot R^2 & \sqrt{3}\cdot R^2 & -\sqrt{3}\cdot R^2 & \sqrt{3}\cdot R^2 \end{bmatrix} \cdot \begin{bmatrix} F_a \\ F_b \\ F_c \\ F_d \\ F_e \\ F_f \end{bmatrix}$$

Fig. 11.18: Prehension force and torque sensing at the robot wrist
1 robot arm, 2 gripper, 3 flange disk, 4 force sensor
F force, *M* moment, *R* radius of the points subjected to force, *h* separation of the attaching points, *L* link beam length.

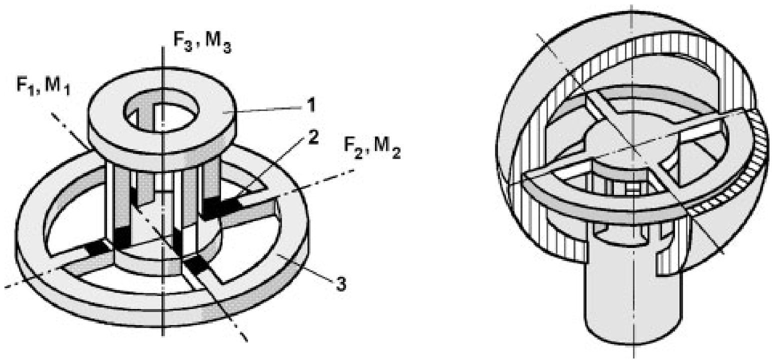
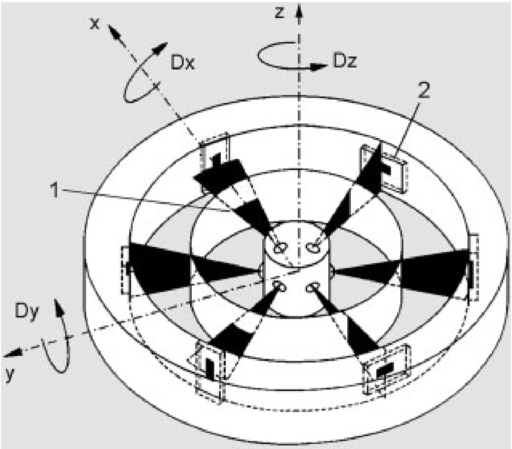


Fig. 11.19: Force-torque sensor with a spoked wheel construction (*DLR*)
1 deformable element, 2 strain gauges, 3 base ring, F_1 force, M_1 moment

direction of major forces can be determined thus allowing the robot to take the necessary corrective action in, for example, an assembly process where a predetermined force limit must not be exceeded.

The choice of strain measurement sensor is not always straight forward. Conventional wire strain gauges are relatively insensitive but enjoy a comparatively low, and usually linear, temperature dependence. On the other hand, semiconductor strain gauges can be several hundred times more sensitive but suffer from much greater, and non-linear, temperature dependence. Figure 11.20 shows a six-component force-torque sensor based on optoelectronic elements [11-12] which are not temperature sensitive. Further advantages lie in their better immunity to electromagnetic fields, contamination, and component tolerances.

The main components are fixed LEDs, moving apertures and fixed PSDs. The six LEDs arranged with an angular separation of 60° have their line of sight towards the external cyl-



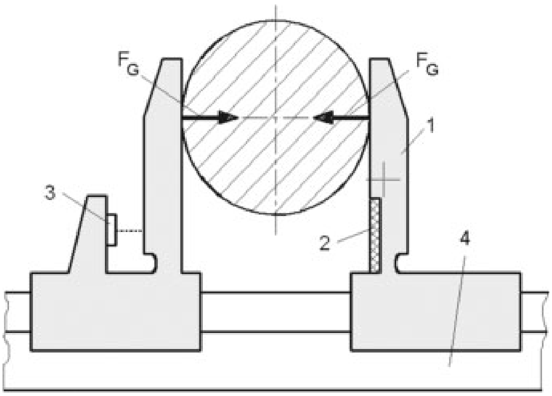
1 slit aperture
2 optical position sensitive detector (PSD)

D angular motion
x, y, z sensor frame

Fig. 11.20: Principle of an opto-electronic force-torque sensor (*DLR*)

inder by which the six moving slit apertures are illuminated. The latter are mechanically coupled to a mechanism which senses forces and moments. The motion of the slit apertures modifies the light line emitted by the LEDs, i.e. controlling the illumination of the six PSDs. The symmetric arrangement of the separate modules allows conversion of spatial deflections in the x-, y- and z-direction and the corresponding rotations *D*x, *D*y and *D*z into electrical signals which are transmitted over a parallel interface to deliver Cartesian spatial coordinates.

In many cases it is sufficient to measure the prehension force directly at the gripper finger tips by the attachment of appropriate sensors. The gripping force F_G can be determined from the deformation of the gripper finger under stress, i.e. during the process of prehension. Figure 11.21 shows two possible configurations for this. In the first example (right finger) the finger deformation is measured by a strain gauge and in the second example (left finger) the measurement of the gripping force F_G is derived from a distance measurement.



1 finger
2 strain gauges
3 distance sensor
4 gripper housing

Fig. 11.21: Strain measurement by distance change (left) or with a strain gage (right)

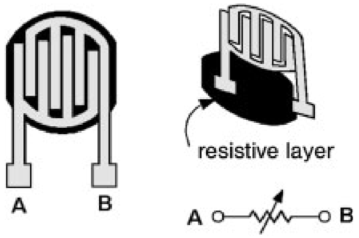


Fig. 11.22: Force sensing resistor (*Interlink*)

Piezo-resistive sensors can also be integrated in a cost effective and space-saving design. These are strain gauges based on semiconducting polymer technology (thin film technique) which are deposited on a membrane. One such example is shown schematically in Figure 11.22.

Although such piezo-resistive elements do not posses the same accuracy and repeatability as wire metal strain gauges, they are extremely cost effective. The overall expensive of wire strain gauge systems lies largely in the necessary amplification and signal processing. This is far simpler for piezo-resistive systems which enjoy a much larger dynamic range. The disadvantage is the logarithmic response, though the hysteresis and long term stability are good even after millions of measurement cycles [11-13].

11.2.4 Finger Position Measurement

In handling and mounting processes it is important to be able to determine whether a planned prehension operation has indeed been carried out successfully. The failure of one operation can result in a chain reaction of consequences leading to complete process failure. Monitoring can be carried out either during the prehension operation or immediately thereafter. These two criteria are explained with the help of Figure 11.23.

Confirmation of prehension can simply consist of monitoring gripper jaw closure, i.e. the function of the gripper itself. Given an object whose size prevents full jaw closure, then

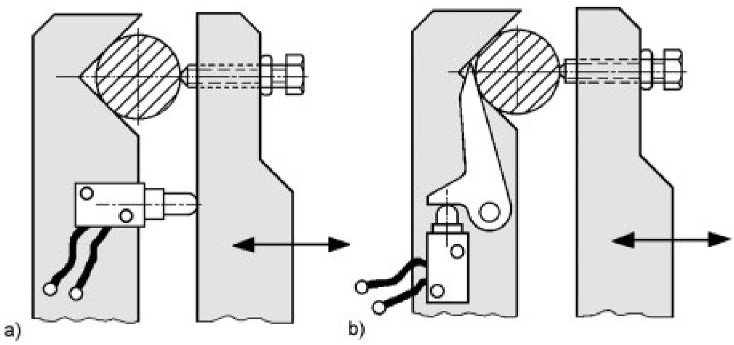


Fig. 11.23: Prehesion/release monitoring
a) acquisition/release detection, b) reliable release detection

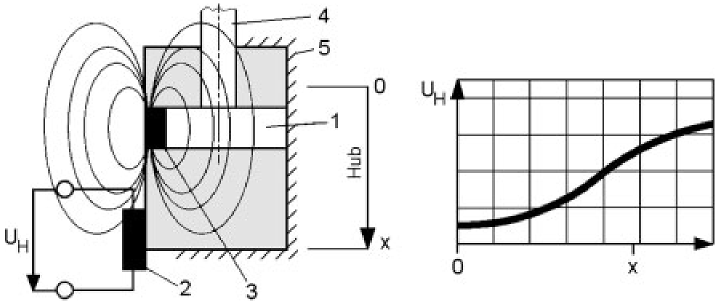
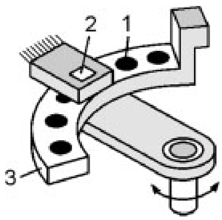


Fig. 11.24: Principle of gripper position monitoring using a Hall-sensor (*Festo*)
1 pneumatic piston for actuation of the gripper jaw, 2 Hall-sensor, 3 permanent magnet
U_H Hall-voltage, x piston travel

detection of partial closure is indicative of object presence (Fig. 11.23 a). In addition, object release may be detected by a similar sensor directly in contact with the object (Fig. 11.23 b).

Although the configuration in Figure 11.23 a) can be used to indicate opening of the jaws it does not guarantee that the object has been successfully released. In modern systems non-contact methods are often preferred. The piston travel of a pneumatically driven gripper can be monitored by a Hall-sensor as shown in Figure 11.24. By external detection of the magnetic field from a magnet integrated into the drive piston, intermediate positions can be interpolated with reasonable accuracy by [11-14].

The resulting Hall-voltage, available as an electrical output, is a function of the travel position. Motions along a curved path can be monitored in angular steps if several magnet elements are integrated into a pivoted segment. This is illustrated in Fig. 11.25



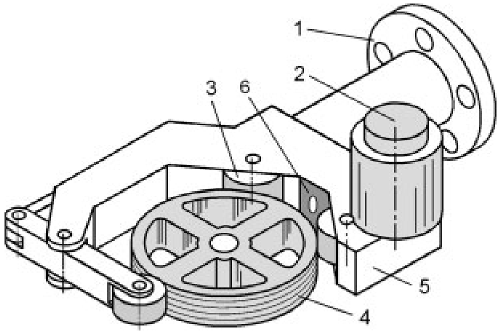
1 magnet
2 Hall-sensor
3 gripper finger

Fig. 11.25: Angular measurement using a Hall-sensor

11.2.5
Measuring Procedures in the Gripper

On line product inspection is an important feature of most modern manufacturing plants. Evaluation of certain parameters directly in the gripper can expedite processes thereby reducing overall manufacturing costs. In addition to the determination of deviations in dimensional parameters, detection of slippage within the gripper is important.

This is particularly prevalent in situations where workpieces are not dry and clean. One example of such a measurement task is presented in Figure 11.27 where a drive mecha-



1 flange
2 drive motor for rotation of the workpiece
3 pin roller
4 workpiece
5 gripper housing
6 measuring device

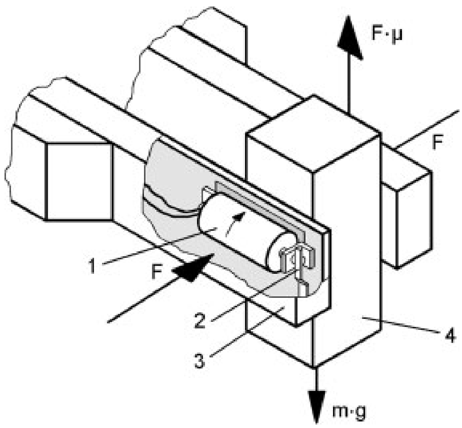
Fig. 11.26: Rotating gripper with integrated measuring unit

nism rotates the workpiece in the gripper. By this means, deviations from the ideal cylindrical profile may be measured.

Slip of an object between the gripper jaws can be detected by specially designed slip sensors. The object may be retained using the smallest possible force and upon detection of sliding (slip) this force can be automatically increased. Figure 11.27 shows the integration of such a (tactile) sensor inside the gripper jaw. The tactile element comprises a roller, the rotation of which is electronically detected thus transmitting a signal at the onset of slippage. Slip sensors are indispensable for the design of adaptive gripping systems intended for the manipulation of very sensitive and easily deformable parts.

Mounting operations often require the movement of the gripper into an exact position within some radial tolerance. This is often required in assembly operations of the "peg in hole" type. Orientation of optical sensors directly along the axis to be traversed would be optimal but in many cases not realizable because the gripper is located there [11-16]. The examples illustrated in Figure 11.28 demonstrate two possible approaches:

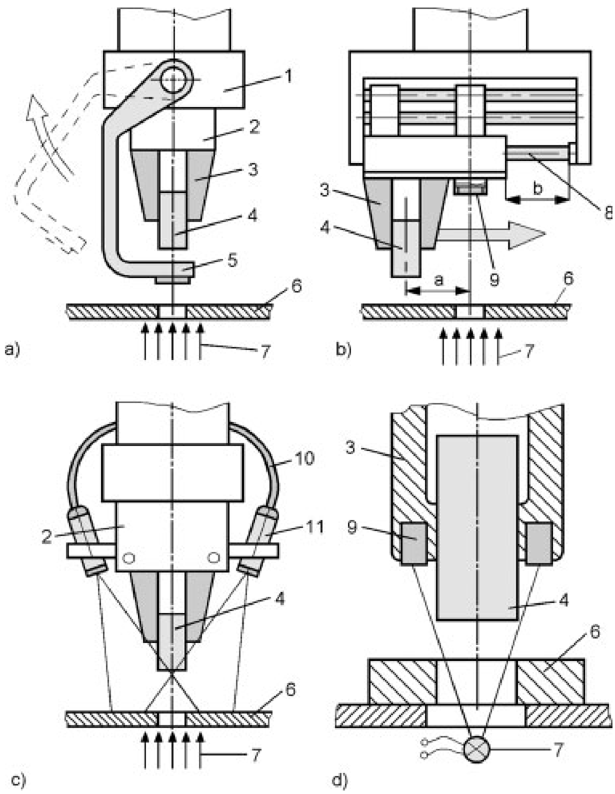
- Moving the sensor away once the target position has been located.
- Lateral installation of sensors directed towards the axis of interest.



1 roller
2 rotation sensitive detector
3 gripper finger
4 workpiece

F impactive force
g gravitational acceleration
m workpiece mass
μ friction coefficient

Fig. 11.27: Slip sensor [11-15]



1 intermediate flange with sensor mounting
2 gripper
3 gripper jaws
4 workpiece
5 sensor retaining bracket
6 base
7 illumination
8 short stroke unit for lateral motion
9 position sensor, e.g. PSD
10 optical fibre
11 integrated sensor (PSD)

Fig. 11.28: Examples of sensor integration for the detection of target positions in mounting operations
a) deviation sensor
b) relocatable sensor
c) external sensor
d) integrated sensor

Unfortunately, pivot mechanisms require more free space, and demand a higher premium on time overheads, than a gripper with integrated sensors.

11.3 Sensory Integration

Metaphorically speaking the robot is equipped with "hand and brain" which distinguishes it from simple handling equipment. "Cognitive robotics" deals with the provision of simple or more complex senses (vision, hearing and feeling) to the robots through additional sensor equipment [11-17].

All robot systems must interact with sensors interfacing with the physical environment. However, sense parameters manifest themselves in different forms at different levels of manipulator activity, which is in turn reflected in the structure of the corresponding level of programming abstraction. Over the past two decades a number of attempts have been made to formulate robot programming levels [11-18, 11-19] and their correspondence to sensor data [11-20] with varying degrees of success. Though names given may vary, in most cases *Joint, Manipulator, Object* and *Task* are agreed as the four effective levels of robot programming. Naturally sensor data is the same but the form in which it is used or made available is different at each level.

- **Joint level**
  Lower level programming, i.e., Geometrical translations as would be carried out with a lower level programming language or PLC system (unseen by the operator of a high level robot programming language). Data in the form of direct sensor outputs, i.e., Binary sensor data, analogue output levels etc.

- **Manipulator level**
  True high level robot programming language commands. Data in the form of information relevant to the high level programming language used such as actual signal input lines on which Boolean and other operations can be performed.

- **Object level**
  Complete program routines and modules. Data in the form of decisions as a result of sensor fusion.

- **Task level**
  Intelligently combined modules under dynamic control organised to achieve a complete task. Data no longer simple – information useful to reasoning processes and analysis.

Most modern robot programming, particularly those parts containing algorithms concerned with prehension, is carried out at the manipulator and object levels. The robot controller (working at manipulator level) sees only input lines as "high" or "low" and so is eminently suited to integration with proximity sensors and other binary output transducers.

At object level, sensor data is in the form of decisions resulting from an overall sensing strategy, not usually the outputs of individual sensors. For example, there may be several sensors all of whose outputs must be combined to give a decision as to the success or failure of some operation. The object level is concerned only with this final decision and not the individual measurands themselves. This allows object level programming to be conducted without detailed consideration of actual physical sensor implementations.

11.3.1 Discrete and Continuous Sensing

Continuous sensing is distinguished from discrete by the fact that "continuous" means that the sensor(s) in question are monitored continuously (though in practice this will usually mean they are interrogated at regular intervals) rather than at the beginning and/or end of a program routine.

In discrete sensing the required parameter may be sensed continuously, but interrogated only at the required stage in the program execution. In a continuously sensed system, the workcell/robot controller is informed the instance the change in the sense parameter occurs, allowing the controller to act immediately. Under these conditions, the sense parameter is no longer the sensor measurand itself but the existence of change in the measurand, either with respect to time or some other pre-determined reference. This is known as sensor transition driven programming which lends itself well to modelling in both Petri-net and flowgraph formats [11-21].

Given a binary sensor, the parameter under continuous sensing conditions is the change in logic level. If used correctly, this attribute can have considerable advantages. A rather inefficient approach would be to sequentially interrogate the sensors continuously in an attempt to detect changes in a sensor. A more astute idea is to let the sensors interrupt the controller in the event of a change in any of the sense parameters. The controller can then interrogate all the relevant sensors once and act accordingly.

11.3.2 Software and Hardware Interrupts

These are available on all computers but usually accessible to the user only for very drastic actions like 'reset'. Lower priority, or maskable, interrupts are sometimes available to the user via some form of input/output mechanism, i.e. the 'break' key on a keyboard. In the case of robot control computers, higher level interrupts are rarely (if ever) accessible to the user. Fortunately most languages have some form of software capability which has the same effect (though without the instant response of hardware interrupts) available through the I/O system, for example the "REACTI" command in VAL II or V+, or "MONITOR" in IBMs AML. In both cases a window time of approximately 20 mS is required, which is not particularly fast when compared with normal robot joint operating velocities.

11.3.3 Sensor Fusion

Sensor fusion is the name given to the tupling or merging of sensor outputs. This can be done at the hardware or software levels, though the result is effectively the same. Given a number of sensors outputs, they may be combined so as to give a set of possible outcomes (in the form of an 8-bit word, for example). Each outcome is unique to a possible state of afairs vis-à-vis the robot gripper and the object to be moved. This can be a very efficient way of providing sensory data to the robot controller. However, the whole is not always greater than the sum of its components parts – only when their combination is correctly organised! For example, an optical proximity sensor which detects the top of a table as the robot gripper descends to grasp an object may be redundant after part acquisition and thereafter the data from a force sensor more valuable in detecting slip during transportation. In this case the optical proximity sensor serves only as a potential source of noise (misinformation) and should be ignored. The act of prehension is always a function of time. Inevitable changes in sensor data during the acquisition process means that any sensor fusion strategy must also be temporally dynamic. For an in-depth discussion and analysis of sensor fusion the interested readers should consult the work by *Durrant-Whyte* [11-22] and similar authors.

11.4 Gripper Control

As a rule the controller of the handling machine, e.g. the robot controller, is also responsible for the control of the end effectors. This can be realized also in conjunction with sensors which are integrated into the gripper.

The control of the gripper is accompanied by monitoring of the motion sequence and synchronization of individual operations between the gripper and the object in accordance with the given program. The following gripper functions may be monitored and/or controlled depending on the job specifications:

- Prehension force and movement (gripper jaw motion).
- Prehension speed.
- Post prehension workpiece presence monitoring.
- Position and orientation of the object between the gripper jaws.
- Forces and moments during the manipulation sequence.
- Measurement of specific workpiece details (special case).
- Identification of the prehension point (camera guided prehension).
- Gripper temperature (special conditions).

Multi finger grippers designed for delicate mounting operations, which do not proceed along a fixed trajectory and are so compicated that they can be performed at present only by operators, require intelligent control. Only then is it possible to achieve adaptive dynamic prehension with constant interpretation of the finger to object contact [11-23 to 11-25].

11.4.1 Control of Pneumatically Driven Grippers

The control of pneumatic grippers is usually restricted to opening and closing of the gripper jaws, activation of additional functions such as gripper jaw rotation, or the connection of additional wrist axes and in rare cases prehension force adjustment by pressure variation.

The control is different for single and double acting pneumatic cylinders. In addition, whether the gripping force should be maintained or not in the case of power failure should be considered. Figure 11.29 shows several examples of standard solutions based on electrically energized 5/2-directional valves.

For the gripper depicted in Figure 11.29 a, any motion that has already commenced will be completed after cessation through the emergency stop switch. For the scheme shown in Figure 11.29 c the workpiece will be retained in the case of emergency stop or power failure. The scheme in Figure 11.29 d offers the additional option of adjusting the speed by means of non-return throttle valves.

The designation of the connections to the directional valves is specified by standard DIN 5590 (1 (P) compressed air connection; 4, 2 (A, B) control or output line; 5, 3 (R) ventilation; 12, 14 (Pz) control connectors). One distinguishes between monostable and bistable directional valves. In monostable valves, which normally contain a reset spring, the valve piston is returned to its initial position once the signal is interrupted. Bistable valves preserve their state even if the signal is switched off. They may be reversed only on receipt of a second (or separate return) signal.

In order to set the gripping force one can limit the pressure. A simplified configuration is shown in Figure 11.30.

As already explained in Section 3.1.2, the use of pressure regulation is always good practice. Not only can gripping forces be limited but the lifetime of a gripper can be considerably increased.

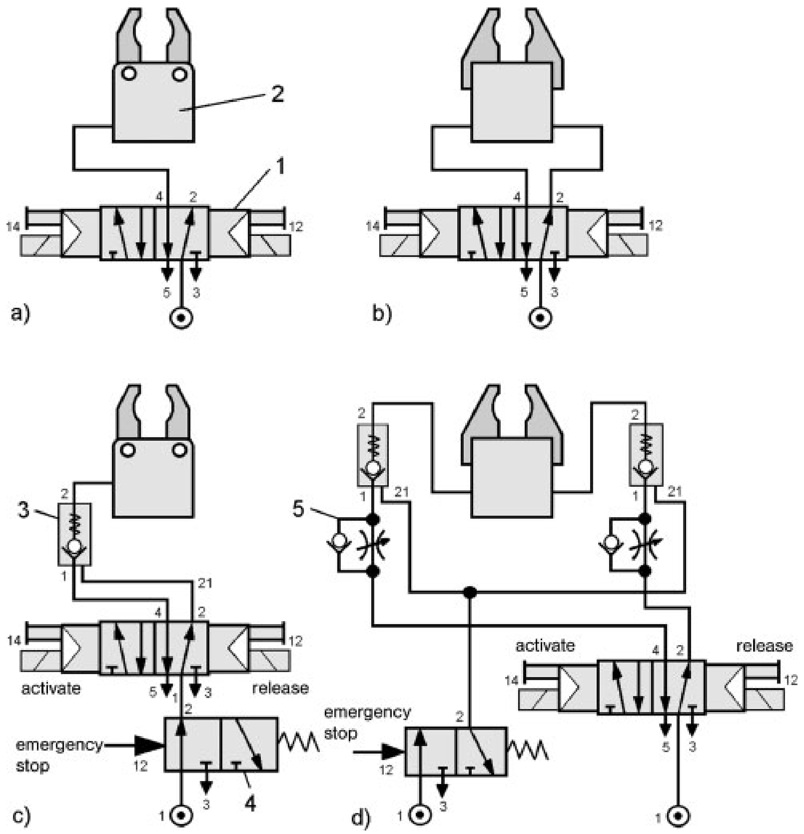
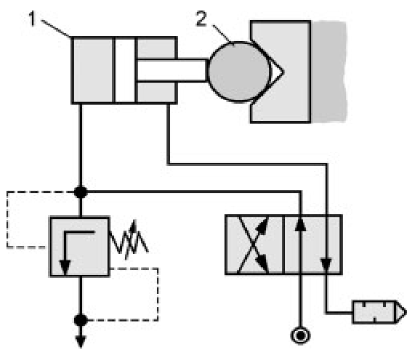


Fig. 11.29: Control of pneumatically driven impactive grippers
a) single acting gripper drive, b) double acting gripper drive, c) maintenance of prehension force in case of power failure, d) gripper with adjustable velocities
1 electrically energized 5/2-directional valve, 2 gripper, 3 return valve, 4 emergency stop valve, pneumatically controlled 3/2 directional valve with reset spring, 5 unidirectional restrictor valve for velocity adjustment

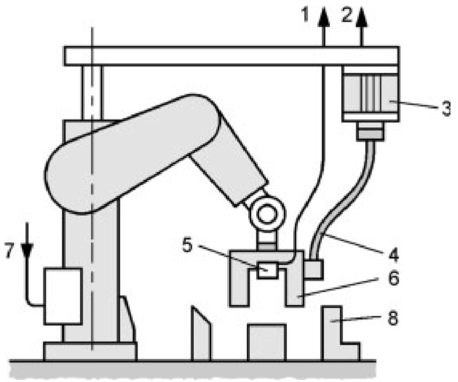


1 pneumatic cylinder
2 object

Fig. 11.30: Limiting of gripping force

11.4.2 Control of Electrically Driven Grippers

Although sensors were used in telemanipulators with force feedback as early as 1948, they were introduced in the control of prehension systems for the first time in 1967. One of the first examples of multi-sensory grippers was realized in the framework of a research project in 1986 [11-26]. It contained a combination of an ultrasound and image sensors as can be seen in Figure 11.31.



1 ultrasound signal data
2 image data
3 camera
4 glass fibre bundle
5 ultrasound sensor
6 gripper
7 robot control data
8 object

Fig. 11.31: Sensory gripper (1986)

The camera, in conjunction with the glass fibre bundle, constitutes an eye-hand-system. The image data is entered into an image processing system which identifies the part and determines its position in the x-y frame. The result is passed on to a computer which defines further operations. The ultrasound sensor measures the distance to the object and the result is used to adjust the correct separation of the optical fibre bundle to the scene in order to obtain a sharper image. A sensor matrix, e.g. with 16 tactile sensors in the gripper jaw surface, determines the position of prehension contact points. It is possible to compile a functional logic table in order to determine the necessary adjustment motions for the robot.

12
Tool Exchange and Reconfigurability

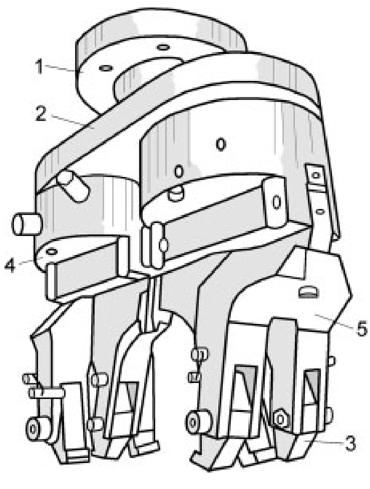
12.1
Multiple Grippers

12.1.1
Double and Multiple Grippers

Double grippers consist of two separate, independently controllable single grippers which are usually coupled by a rotation or swivel unit or are mounted on a common plate.

- **Double grippers:** temporal and functional prehension of two objects independently.
- **Multiple grippers:** simultaneously prehension of more than two objects.
- **Dual grippers:** simultaneously prehension of two objects.

Figure 12.1 shows one such example where two angle grippers are connected to the same gripping head. The grippers are pneumatically (or hydraulically) driven. In the hydraulic case the prehension forces are larger but cycle times tend to be longer compared to pneumatic versions. The gripper jaws are pivoted so that they can adjust themselves to the workpiece. Each side is formed as a double finger which mimics the function of a thumb.



1 flange
2 gripper bridge
3 gripper jaw
4 two-jaw angle gripper
5 double finger

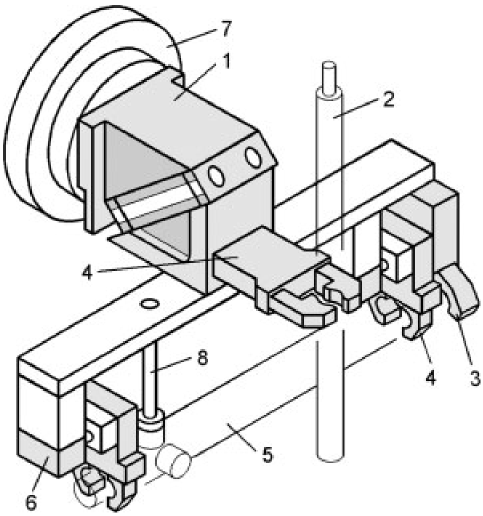
Fig. 12.1: Angle grippers combined into a double gripper head (*Röhm*)

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

ISBN: 978-3-527-40619-7

The double grippers are employed in feed operations for the simultaneous movement of raw and pre-fabricated parts. This saves time because it avoids the need for two redundant movements between the magazine and the clamping fixture per feed cycle by simultaneously acquiring the blank and the pre-fabricated part.

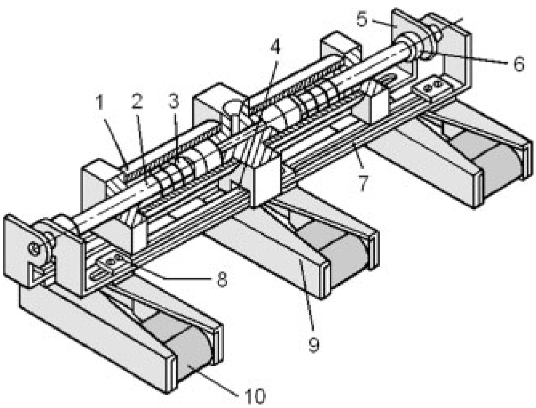
A similar unit which is a combination of three parallel grippers is shown in Figure 12.2. It is designed for the simultaneous prehension of both a universal shaft and its joint housing (total endeffector weight 17 kg).



1 pivot head
2 universal shaft
3 angular gripper
4 parallel gripper
5 universal shaft housing
6 short travel unit
7 flange
8 support pin

Fig. 12.2: Compact gripper for several components (*SCHUNK*)

The angular gripper is used for the adjustment of the housing along its longitudinal axis. Upon adjustment, the gripper jaws are moved with short travel units towards the prehension points. In addition, a pivot head can rotate the entire gripping unit by 180° about an inclined axis. This allows for further spatial orientation of retained objects.

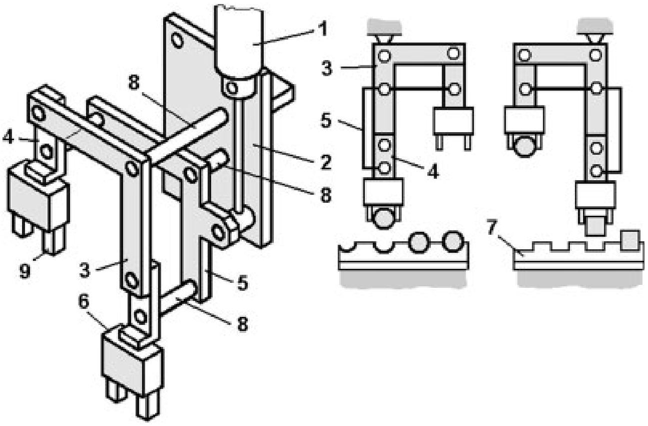


1 pneumatic cylinder
2 piston rod
3 helical spring
4 clamping nut for gripper jaws
5 rear slide
6 adjustment ring
7 rail slider
8 fixation plate
9 gripper jaw
10 workpiece

Fig. 12.3: Triple gripper (Russian Patent 623 734)

Figure 12.3 shows a gripper which can accept three identical parts with a single prehension stroke. The gripper consists of two pneumatically actuated rail sliders. One rail controls the right hand gripper jaws and the other the left hand ones. Application of compressed air opens the gripper jaws and retention is realized by spring force. Within the physical capacity of the mechanism, any number of gripper jaws can be mounted onto the rail slider at any arbitrary position. The impactive stroke is equal for all grippers. In order to compensate for the workpiece tolerances, the usual shape mating or addition of compliant surfaces to the gripper fingers may be utilised.

Figure 12.4 shows a simplified representation of a double gripper with an unusual slewing unit. The grippers are always guided parallel to one another by means of an angle lever system.



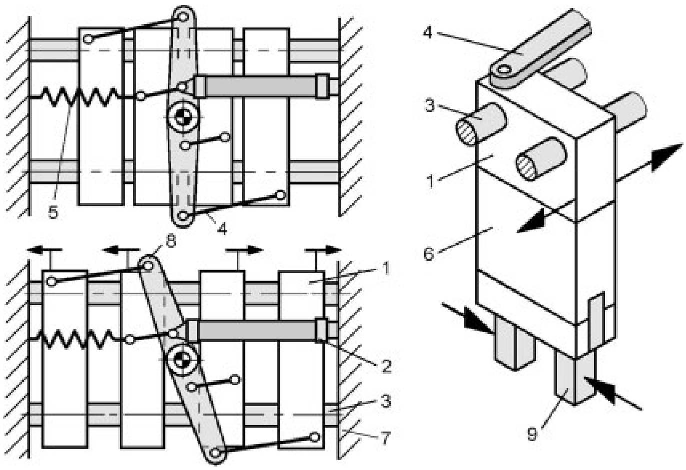
1 pivot cylinder
2 baseplate
3 angle arm
4 coupling bar
5 angle lever
6 parallel gripper
7 magazine
8 rotary axis
9 gripper jaw

Fig. 12.4: Double gripper with slewing unit (*Röhm*)

This allows for synchronous movement of raw and pre-fabricated parts within a small space. Sufficient positional accuracy is maintained without additional axial motion of the handling system.

The grippers can also be equipped with rotary jaws which permit the rotation of the retained workpieces by 90° or 180°. An essential argument for the employment of such grippers in preference to turret systems is the resulting interference contour of the entire manipulation system. The rather narrow design, together with the exclusive use of swivel joints in the mechanics is another advantage associated with production technology.

Figure 12.5 shows the principle of a multiple gripper which can prehend four objects and then change the separation between the individual grippers. These can be objects having a defined separation on the conveyor belt. Upon prehension, the slide blocks will move inwards so that the parts are lying close to each other at the point of deposition (e.g. a flat pallet). Adjustment may be realized by a servo motor acting on the swing-wing. In the case of prime movers in the form of pneumatic of hydraulic muscle systems, the separation of the slide blocks and hence that of the acquired objects can be adjusted according to the pressure. Instead of the tension spring, the employment of a second muscle is possible.

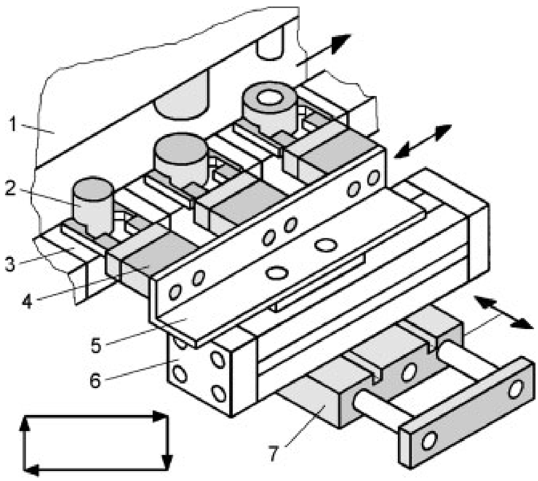


1 slide block
2 fluid muscle
3 double round guide
4 lever
5 tension spring
6 single gripper
7 gripper housing
8 swing-wing
9 gripper jaw

Fig. 12.5: Displacing gripper with fluid muscle actuation (schematic diagram after *Weber & Winter*)

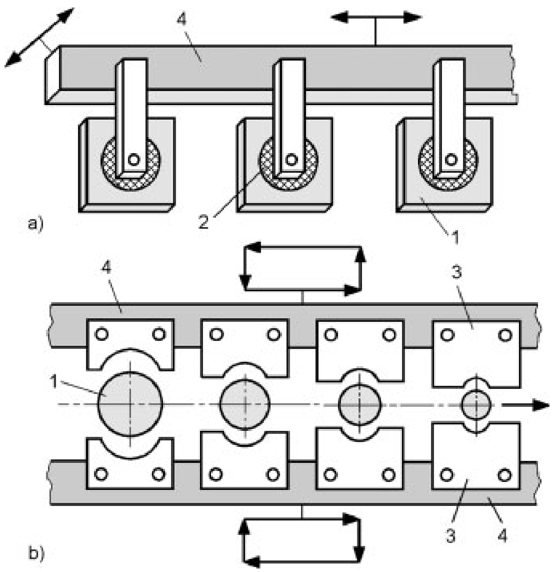
12.1.2
Multiple Gripper Transfer Rails

Pressing and forming is normally carried out using a variety of machines with transport between processes being necessary. Modern large commercial presses normally contain transfer equipment as an integral part of their design. For smaller presses or special solutions it is possible to employ a multiple gripper system using standard pneumatic components as illustrated in Figure 12.6. This equipment consists of several single grippers attached to a transfer rail. It is possible to avoid the necessity of a transverse stroke axis if wide aperture angle grippers are used.



1 press
2 workpiece
3 underside of workpiece
4 gripper
5 transfer rail
6 linear actuator (rodless cylinder)
7 short stroke actuator

Fig. 12.6: Two-axis transfer equipment



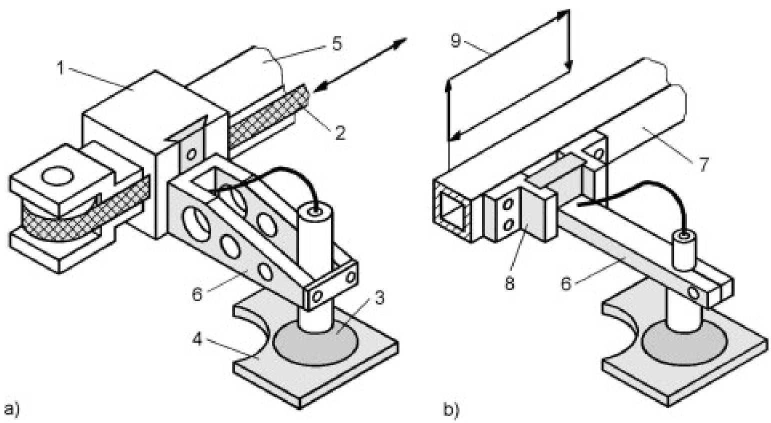
1 workpiece
2 suction cap
3 gripper jaw
4 rail

Fig. 12.7: Transfer equipment
a) 1-rail system
b) 2-rail system

All workpieces are simultaneously gripped and passed on in one linear transport step. The mass of the grippers and their rails should be as small as possible in order to enable short cycle times. Two common methods are known as 1-rail and 2-rail systems (Fig. 12.7).

The 1-rail system is suitable for low mass objects, with for example vacuum suction, and travel rages of up to 3 m. The achievable travel speed is typically between 2 and 5 m/s. There are two basic methods involved. The carriage principle where the grippers are the only moving parts and may be demountable and transfer is realized by synchronous belts or steel bands. The bar principle, in which rigid arms are allowed to move in two axes [12-1].

Some design examples can be seen in Figure 12.8. In 2-rail systems the workpieces are held between the gripper jaws and transported in discrete steps.



1 carriage
2 steel band
3 suction cap
4 workpiece
5 rail profile
6 arm
7 running rail
8 holder
9 motion cycle

Fig. 12.8: Different designs of lifting beam transfer gripper equipment
a) carriage principle, b) bar principle

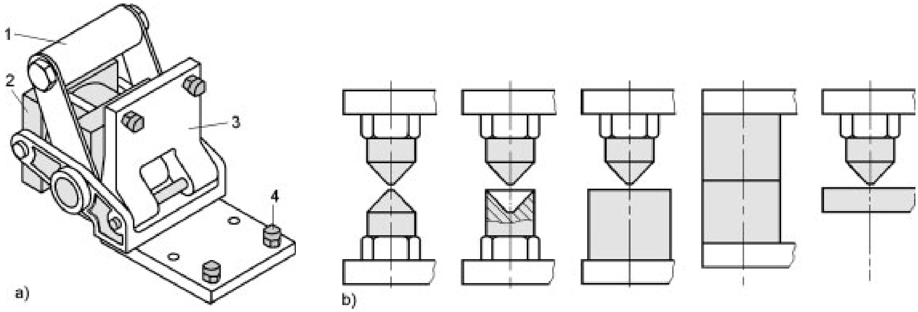


Fig. 12.9: Transfer press clamping (*Bilsing*)
a) general view, b) jaw combinations
1 holder, 2 pneumatic cylinder, 3 swivel plate, 4 clamping spike

The gripper jaws must always be adapted to the workpiece dimensions because there is only one constant closing stroke. It is often sufficient if the parts are prehended simply by shape mating. Figure 12.9 shows a typical impactive gripper used for prehending sheet metal parts at the edges.

As illustrated in Fig. 12.9, different jaw profiles may be employed to ensure a firm grip.

12.1.3 Turrets

Turret grippers can prehend two or more, identical or different, objects independently. Compared to the previously mentioned forms of composite and multiple prehension devices, turrets are restricted to sequential operations and represent a reasonable alternative to gripper exchange systems. They are used primarily in automated assembly and are intended for the manipulation of relatively small and light workpieces. Technically they can be regarded as a combination of several separate grippers with an additional rotary wrist unit. Many different arrangements are possible and Figure 12.10 shows some designs and

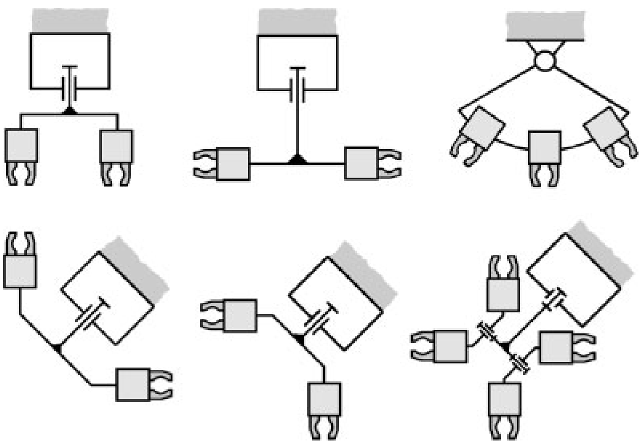


Fig. 12.10: Turret gripper configurations

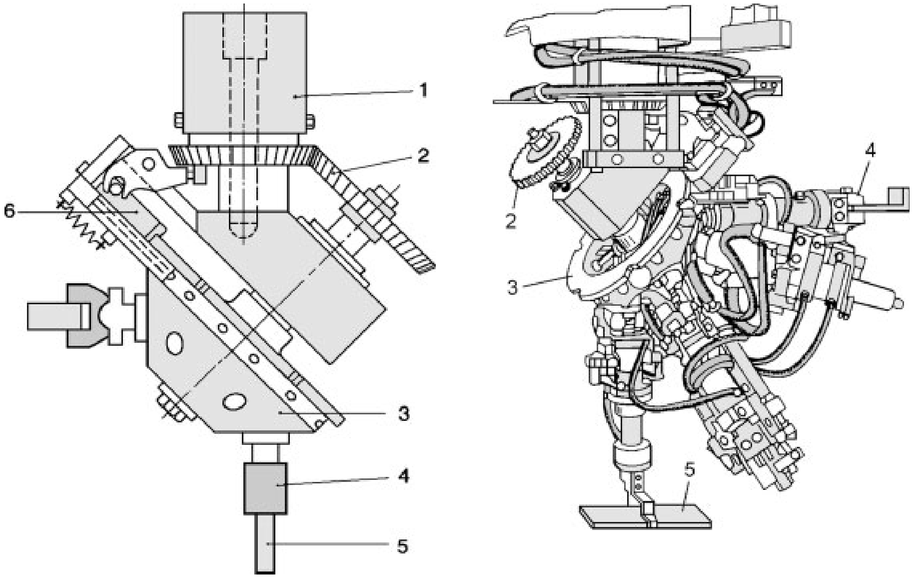


Fig. 12.11: Turret with six separate grippers and joining tools (*Sony*)
1 adaptor, 2 bevel gear, 3 crown turret, 4 gripper, 5 object, 6 lock mechanism

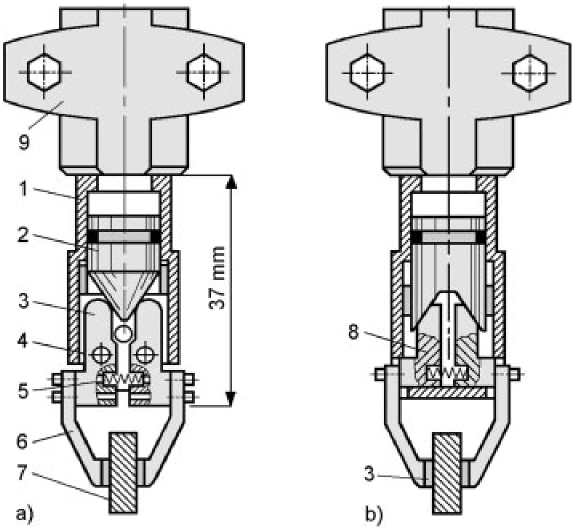
their respective principles. Selection of the next gripper by rotation of the turret usually takes less than a second. One advantage of the turret gripper lies in the ability to acquire a number of objects at times when the robot is otherwise idle. These may then be rapidly brought to their respective destinations as required thus eliminating much deadtime.

Turrets can normally carry between 2 and 6 separate grippers. Together with the workpieces they are holding this makes a rather bulky entity with an awkwardly large interference contour. This is particularly well illustrated in the example shown in Figure 12.11.

The special feature of this system is that in addition to the final rotational axis of robot, the turret may also rotate. This is realized by an incremental rotation of the bevel wheels. Depending on the available space the necessary electrical and pneumatic connectors and cables must also be accommodated.

When only two end-effectors are employed a much cheaper alternative is the "half axis". This consists of a simple structure holding two grippers perpendicular to one another. A pneumatic or electrical actuator then simply rotates the structure through an angle of 90° whenever the other gripper is needed. It is effectively a two position version of the turret previously described.

Though somewhat larger than the devices normally termed micrograppers (see Chapter 7), Figure 12.12 shows two designs of pneumatically driven grippers intended for the mounting of very small components. In both these configurations, the pneumatic piston acts directly on the gripper jaws with its internal and external cone surfaces. A (vertical) travel compensation of 5 mm is integrated into the mounting flange. The gripper is intended primarily for assembly use in fine mechanical and electronic sectors. The simple



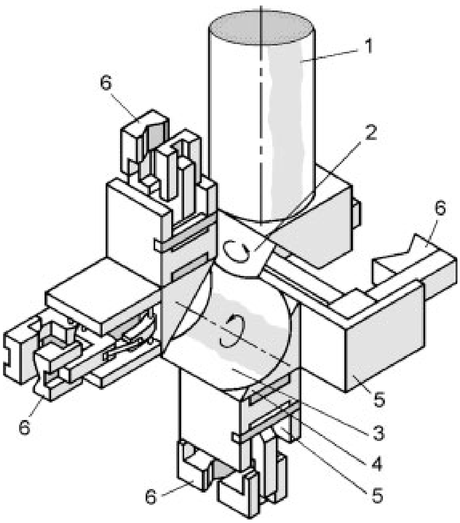
1 housing
2 8 or 12 mm diameter piston
3 gripper jaw
4 cylinder pin
5 tension spring
6 gripper finger
7 workpiece
8 jaw
9 mounting flange with integrated tension spring

Fig. 12.12: Microgripper (*Festo*)
a) angle gripper
b) parallel gripper

design enjoys a very attractive cost-performance ratio and a typical lifetime exceeding twenty million switching cycles.

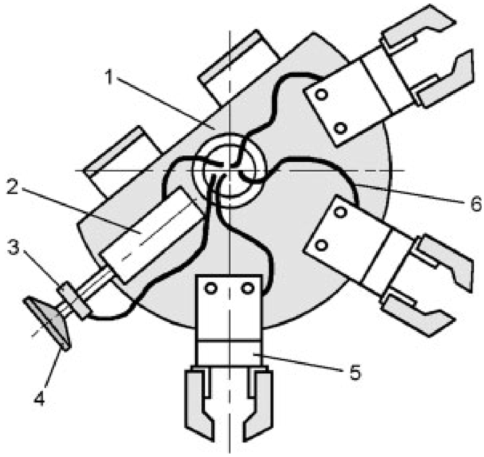
Figure 12.13 shows a simple turret design consisting of two orthogonal 180° slewing units. Each of the 4 grippers can be brought to the required operational position within a very limited collision space.

Turret applications are influenced considerably by the size of the objects to be handled and the related inertial forces. Because it is always necessary to move several grippers, the collision space is substantially larger compared to that needed for single grippers.



1 robot wrist
2 slewing unit
3 second slewing unit
4 gripper flange
5 impactive gripper
6 gripper jaw

Fig. 12.13: Turret with 2 rotational drives [12-2]



1 base disk
2 pneumatic cylinder
3 ejector
4 vacuum suction cup
5 parallel jaw gripper
6 compressed air line

Fig. 12.14: Turret for the handling of different parts

Figure 12.14 shows a design with a horizontal rotational axis. All grippers are driven from compressed air but may be of quite different function. Sufficient free space for collision prevention must be included.

The increased radius of gyration caused by large turret arrangements can lead to additional control problems, particularly with robots having cylindrical work envelopes such as SCARA designs. The additional inertia can cause the robot to become unstable, particularly when the end-effectors mass centre of gravity is located some distance from the robots normal tool centre.

In circumstances where the objects to be handled are particularly small and light such as surface mount component placement, turrets can be extremely cost effective. As depicted in Figure 12.15, a ring of (typically 12 or 18) small and identical pneumatic gripping heads are rotated over component conveyor strips to collect the necessary number of components for a particular task. The robot then moves to the intended destination before depositing the components in the appropriate positions.

Rather than having to employ heavy turrets, suffer the inconvenience of manual change-over or the extra costs and time overheads of automatic re-tooling, the optimal so-

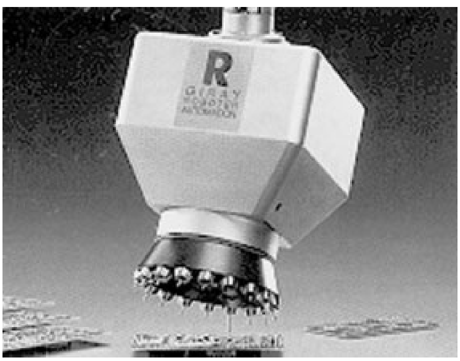


Fig. 12.15: Turret gripper for SMD components (*Giray Roboter Automation*)

lution would be an automatically reconfigurable robot gripper. Unfortunately such flexibility is rarely possible in practice without the addition of extra weight or a significant speed reduction. Nevertheless, there are some designs which come some way towards this ideal.

12.2 Specialized Grippers

12.2.1 Composite Grippers

Composite grippers are multi-purpose grippers in which different types of prehension mechanism are combined into a single gripping unit. One such gripper is shown in Figure 12.16. It possesses two pairs of simultaneously activated grasping organs for internal prehension.

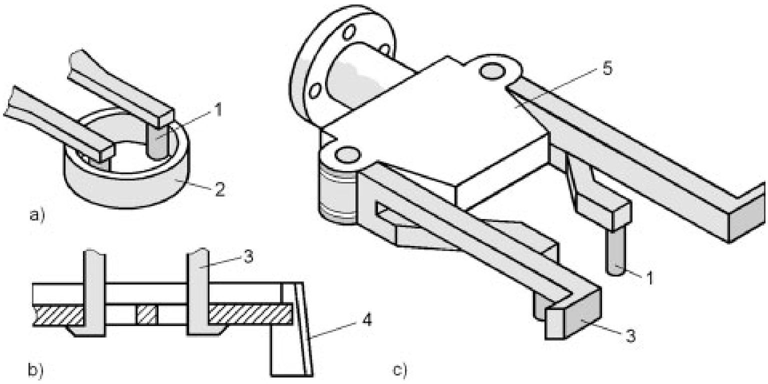
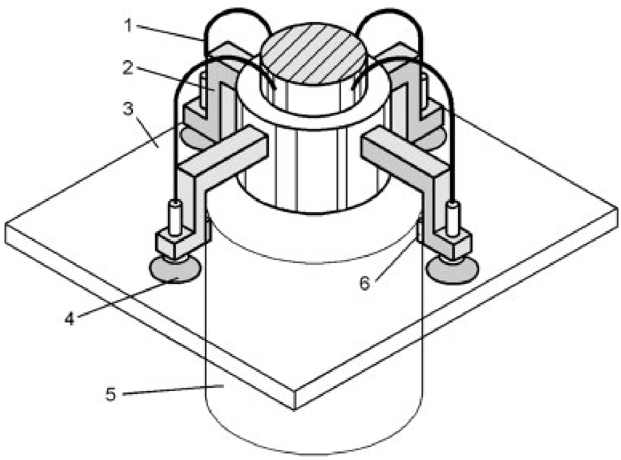


Fig. 12.16: Mechanical impactive gripper for machine loading
a) workpiece prehension, b pallet prehension, c) general view
1 pin for internal grip, 2 workpiece, 3 hooked finger for pallet gripping, 4 pallet, 5 main gripper

The elongated fingers also assist in the manipulation of the empty pallets. To this aim the pallet bottom is provided with corresponding recesses. The advantage is that the robot can operate longer without operator attendance because it is capable itself of grasping and removing the empty pallets. This ensures access to the workpieces from the next pallet on the stack.

Figure 12.17 shows another example of such a design – a four finger gripper.

The gripper shown in Figure 12.17 can perform external prehension whilst its jaws simultaneously have a centring effect, e.g. it can palletize cans. The gripper fingers are additionally equipped with suction cups which provides the option of picking up flat parts from a plane surface. This can be, for example, an intermediate stack plate made from paperboard or plywood overlay to be applied once per palletizing cycle.



1 vacuum air line
2 gripper finger
3 workpiece (flat part)
4 suction cups
5 workpiece (cylindrical part)
6 gripper jaw

Fig. 12.17: Composite gripper

The combination of impactive and astrictive techniques is often implemented for "auxiliary functions". This is illustrated by the next example in Figure 12.18 showing the storing of textile fibre bobbins. The bobbins are internally prehended by the mandrel gripper and deposited onto the pallet. The next layer of the stack requires an intermediate plate which is also provided by the same handling equipment. The intermediate plates are removed from a separate stack. The suction heads used for this purpose are allowed to protrude only when they are required. This eliminates the need for expensive and time consuming gripper exchange systems. The combination can be realized relatively simply by using pneumatic cylinders with hollow piston rods.

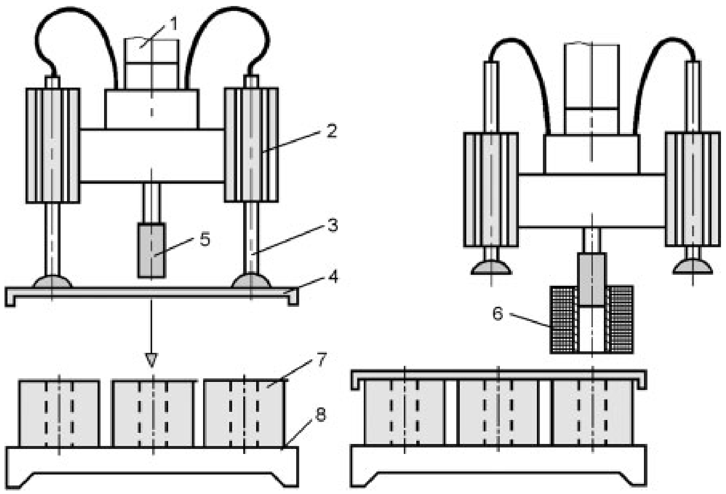
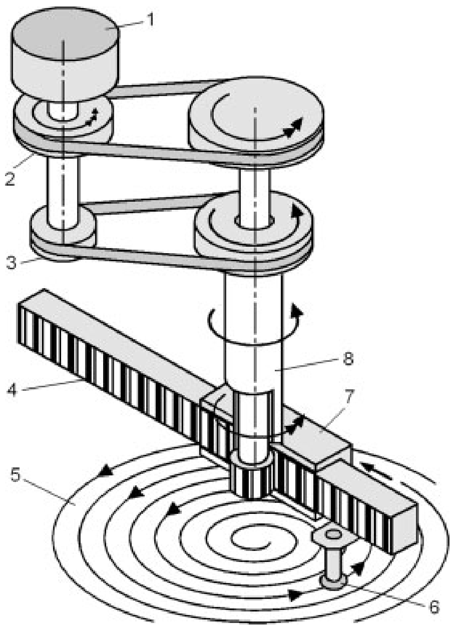


Fig. 12.18: Multilayer storing of textile fibre bobbins with a composite gripper
1 flange, 2 pneumatic cylinder, 3 hollow piston rod, 4 intermediate plate, 5 internal gripper, 6 fibre bobbin, 7 first layer of the stack, 8 transport pallet

12.2.2 Reconfigurable Grippers

Planar astrictive or contigutive designs invariably rely on a considerable degree of redundancy thus necessitating large construction as in the case of grippers intended for the prehension of large fabric panels of varying size [6-14]. The pneumatic alternative is forced to rely on Plenum chambers or complicated pneumatic switching systems. One interesting design, intended for leather handling, is capable of positioning a vacuum suction cup anywhere within a given circular work envelope by means of one rotation and one translation about the tool centre as shown in Figure 12.19. For its intended application (the handling of pre-cut leather parts of varying size) four such gripping heads are mounted on a platform held by the robot [12-3].



1 stepper motor
2 toothed belt gear
3 translational drive
4 toothed rack
5 adjustment range
6 gripper, in this case a suction cap
7 toothed rack guide
8 concentric hollow shaft

Fig. 12.19: Spiral positioning head

Each gripper can be positioned within a given circular area. The grippers are mounted on a base plate which in turn is fixed to the robot flange. The adjustment motion is produced by an electrical stepper motor with angular resolution of 200 steps per revolution. With a maximum speed of 5000 steps per second, the gripper can theoretically be rotated within 40 ms. Transit of the total adjustment range requires 8.5 turns of the spiral gripping unit.

12.2.3
Modular Gripper Systems

Modular solutions offer the maximum possible diversity of gripper combinations. The purpose is for the user to be able to react as rapidly as possible to demanding production changes. The underlying idea is the decomposition of the overall function into several partial functions realizable through module combinations.

The degree of decomposition can be varied widely. Figure 12.20 shows several gripper configurations and their relative decomposition.

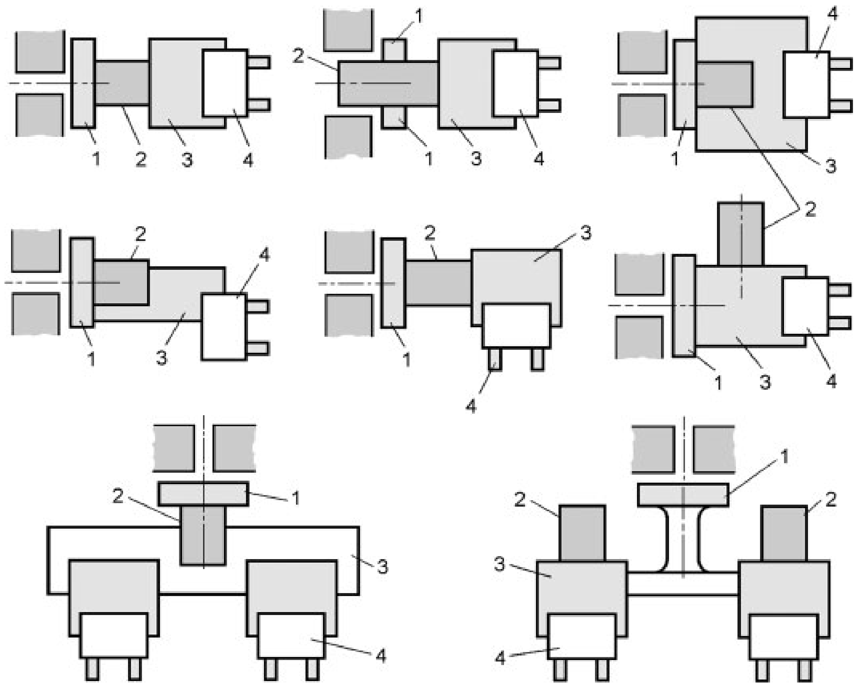


Fig. 12.20: Examples of gripper configurations using modular system components
1 flange, 2 actuation, 3 gear, 4 grippers

Modular systems are of particular interest in cases where a degree of flexibility is demanded but where the resulting downtime for reconfiguration does not justify the expense of automatic exchange systems or turrets. Generic building components may be used to compose multi-grippers suitable for the corresponding task. Figure 12.21 shows several such components typically used for handling masses in the range of 1 kg (ASS).

The modular principle is particularly applicable to impactive grippers where only the fingers need be changed. Figure 12.22 shows a very light design of a gripper system using passively moving jointed fingers.

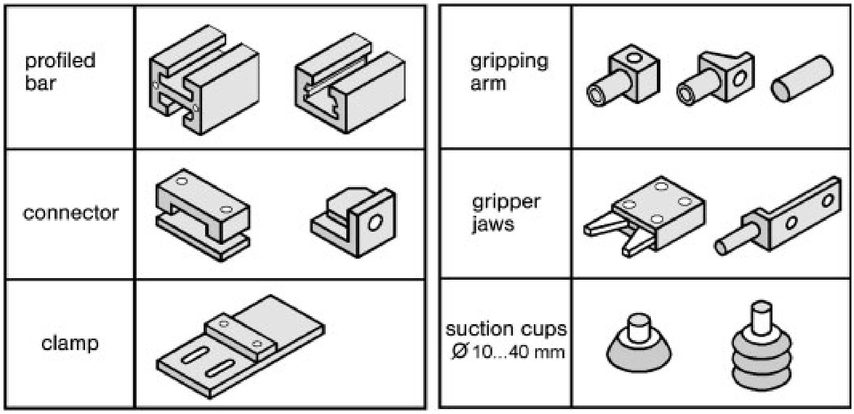


Fig. 12.21: Modular system for robot hands

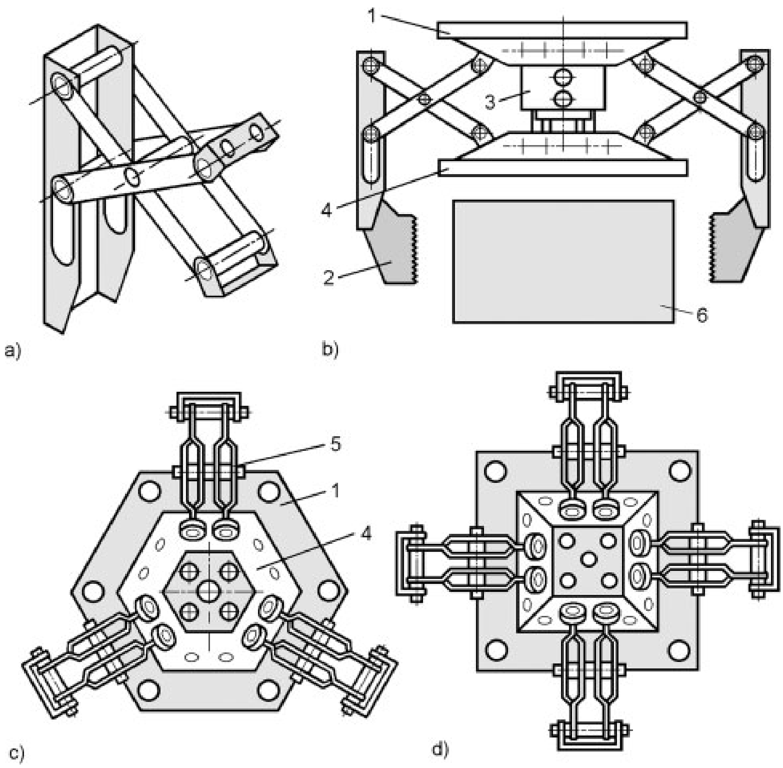


Fig. 12.22: Parallel jaw gripper with modular fingers
a) finger, b) two-finger gripper, c) three-finger gripper – underside view, d) four-finger gripper, 1 base plate, 2 gripper jaw, 3 pneumatic cylinder, 4 stroke plate, 5 joint, 6 workpiece

Modular concepts require a complementary assortment of functional units, compatible interfaces (for mechanics, power supply, and information) and sophisticated, low-maintenance and reliable modules (Fig. 12.23). The most important modules are:

- Main gripper.
- Jaws, as a rule adapted to the workpiece.
- Rotary module.
- Short travel module.
- Pivoting module.
- Gripper exchange system.
- Compensation unit for position and angle errors (remote centre compliance).
- Overload and collision protection module.
- Multiaxial force/torque sensor.

For grippers which are primarily used for machine feeding, additional movement may be required in order to push the part home to achieve final locking (push-click). This function can be fulfilled by adaptable push rods integrated into the gripper (see Fig. 13.13). As can be seen in Figure 12.23 (right), pivoting modules can be also used as a rotary base in the design of double grippers.

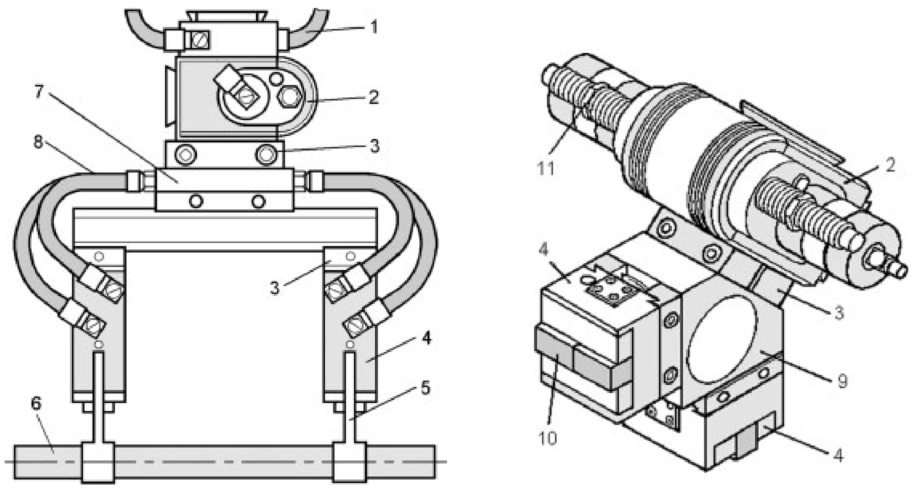


Fig. 12.23: Gripper composed of modular units (*Montech*)
1 compressed air line, 2 rotary unit, 3 clamp element, 4 gripper, 5 gripper finger, 6 workpiece, 7 compressed air manifold, 8 pneumatic connection, 9 connection angle, 10 basic jaw, 11 damper

12.3
Gripper Exchange Systems

Automatic gripper and tool exchange systems considerably improve the flexibility of industrial robots and potentially open up new fields of application. This is an alternative which allows the performance of several successive operations with different end effectors within the same robot workcell. There exist many potential design solutions for the mating of interfaces between gripper and robot and automatic exchange is not always necessary. In fact many, very quick and effective, manually operated exchange systems are in use. Exchange systems are available in many different sizes with diameters ranging from 50 to 220 mm.

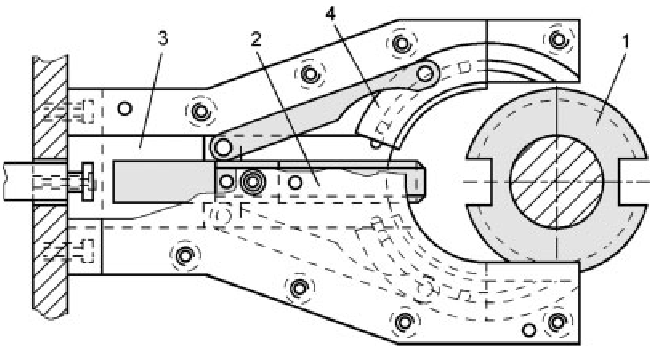
12.3.1
Tool Exchange

In most NC and CNC machines tool exchange is performed automatically. This requires grippers which are adapted to the specific problem and are capable of taking the tool from a disk, chain, or serial magazine and inserting it into the work spindle of the machine. Prehension can be realized by

- a gripping system integrated into the machine (gripping the workpiece shank radially or axially) or
- an industrial robot which can assist in the tool exchange program.

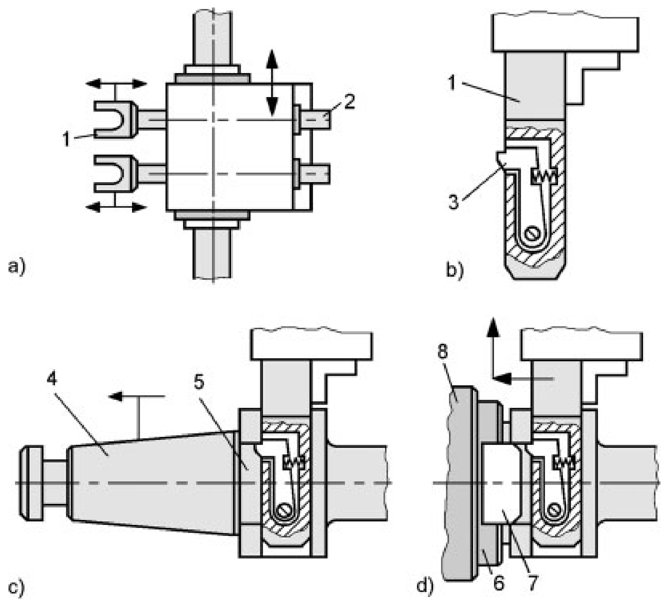
Tool exchange grippers always exploit a common prehension point on the machine tool thus reducing demands on flexibility. The tool shank can be secured in the gripper jaws by using the available profiles (circular rills or grooves).

The orientation of the tool in the gripper depicted in Figure 12.24 is secured by a groove. Once the gripping position is approached the curved segmented jaws are moved into a guide groove achieving shape mating with the ring groove on the workpiece shank.



1 workpiece
2 fixed stop
3 actuation
4 gripper jaw

Fig. 12.24: Impactive gripping unit for tool exchange equipment



1 gripper
2 linear arm
3 locking latch
4 workpiece shaft
5 attachment slot
6 work spindle
7 front in-fit key
8 head stock

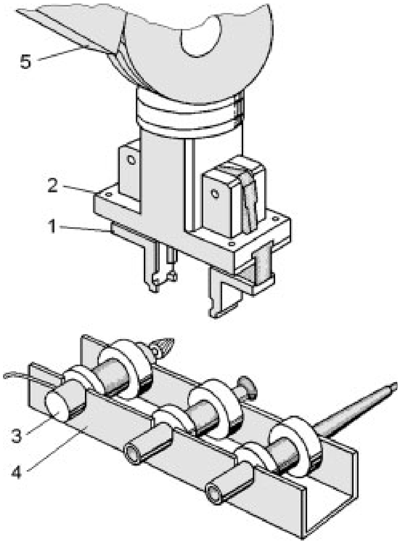
Fig. 12.25: Gripping procedure when exchanging a tool
a) double tool gripper, b) gripper, bifurcate, c) gripper accommodating tool,
d) end of insertion motion

Tool exchange units are often designed as double grippers (revolver principle or parallel gripper arrangement) in order to simultaneously prehend the new tool whilst retaining the last (or next required) tool thus reducing machine dead time. Figure 12.25 demonstrates such a tool exchange process.

The gripper secures the workpiece shaft solely by shape mating. Upon insertion of the U-shaped grasping form a latch is engaged which secures the tool. Release occurs solely through the front in-fit key on the work spindle of the NC machine.

There are also tool exchange systems which rely on force matching. Their design is similar to that of conventional impactive grippers. Since machine tools can be quite heavy the required carrying capacity of tool exchange grippers can be as much as 30 kg or more. For this reason they are often actuated hydraulically and tool exchange is performed within seconds.

Sometimes the design of the gripper jaws makes it possible to handle both the workpieces and the tools without exchanging the gripper, as can be seen in Figure 12.26. In this case the tools possess unified prehension positions, which demands that the tool and the workpieces have similar dimensions at the prehension point. The example in Figure 12.26 shows tools which are only transported by a robot – they are not inserted into the spindle of the machine.



1 gripper jaws
2 gripper
3 workpiece
4 magazine
5 industrial robot

Fig. 12.26: Gripper for tools and workpieces

12.3.2
Task, Functions and Coupling Elements

The exchange system connects an endeffector (gripper, tool, measuring or test instrument) to the robot or manipulator arm with the help of a flange. This coupling ensures:

- Mechanical connection capable of transmitting forces and moments.
- Energy supply to the endeffector (electrical current, compressed air etc.).
- Information flow (sensor signals, measurement data, etc.) and, in some cases.
- Material flow (air and coating materials for spray tools, dyes, coolants and gases for welding apparatus).

In the majority of cases, automatic exchange systems are quite demanding because they must ensure not only an exact mechanical connection but also the transmission of signals, power, and occasionally materials. The exchange system is indispensable in mounting cells where the robot must accept (in alternating cycles) grippers and other tools. The necessary functional elements can be derived from an analysis of the requirements as shown in Figure 12.27.

The following demands are made on power, material, and signal line connectors:

- Small dimensions, small mass.
- High axial accuracy (free from centring play, no misalignment).
- Skew-free acceptance of grippers or tools.
- Non-slip transmission of all transmitted forces and moments.
- Short exchange time and simple motion sequence.
- High reliability, low wear (secure retention even in cases of power failure, long contact lifetime).
- Weak coupling and decoupling forces.

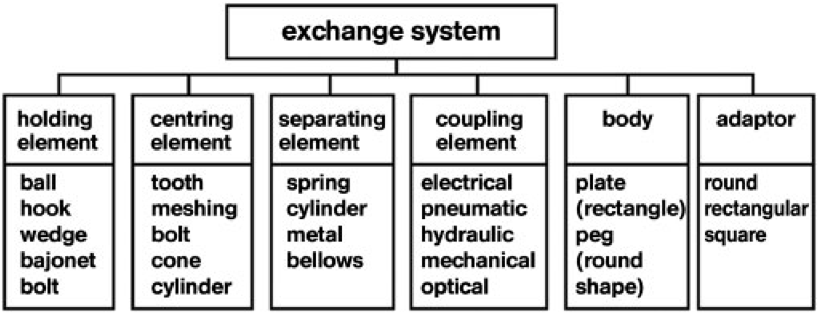


Fig. 12.27: Functional elements of an exchange system

- Coupling preferably by translational motion of coupling elements.
- Small and constant electrical contact resistance (interference free, safety).
- Leakage-free coupling of fluids (lossless transmission).
- Sealability against leakage (coolants and gases) and dirt ingress.
- Compatibility with simple design of storage magazines for grippers and tools.

Mechanical coupling is realized primarily by shape mating of elements with simple shape and high functional safety. The shape mating must ensure simultaneous coupling of power, material, and signal lines and must be capable of working under high pressure. The holding elements must produce a high prehension force whereby a clamping range of 1 to 2 mm is normally sufficient. The locking and unlocking of shape matched coupling elements takes place at the acceptance and/or deposition location through:

- Drive elements (pneumatic cylinder) in the exchange system or at the magazine (e.g. rack drive at the magazine acting on a geared ring at the exchange system) or
- Special motion of the industrial robot interacting with magazine elements (e.g. roller follower at the exchange system and ramp curve at the magazine).

The locking and unlocking motions must be coupled with the actuation of the corresponding connections for the electric power lines and valves for the material lines (coolant, gas, etc.). The locking takes place through cylindrical (bolt), conical, wedge, spherical or curved elements. Successful locking can be confirmed by means of a proximity switch and the locking must remain active in cases of power failure. This can be realized either by a secure self-locking system or by spring force. On unlocking, release of coupling elements must be augmented by force due to the retention forces inherent in the plug and socket and other mechanisms. This is realized either by

- an ejection motion produced by a drive element (pneumatic cylinder),
- directly with compressed air (possible only for a cylindrical shank) or
- retention of the endeffector in the storage magazine by passive or active mechanical elements and appropriate robot motion.

Figure 12.28 shows a small selection of mechanical coupling elements.

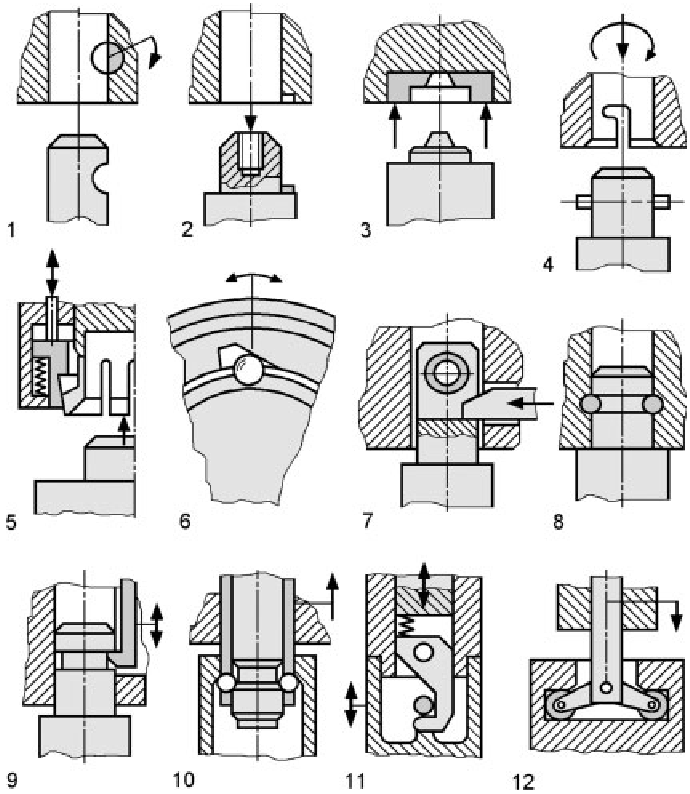
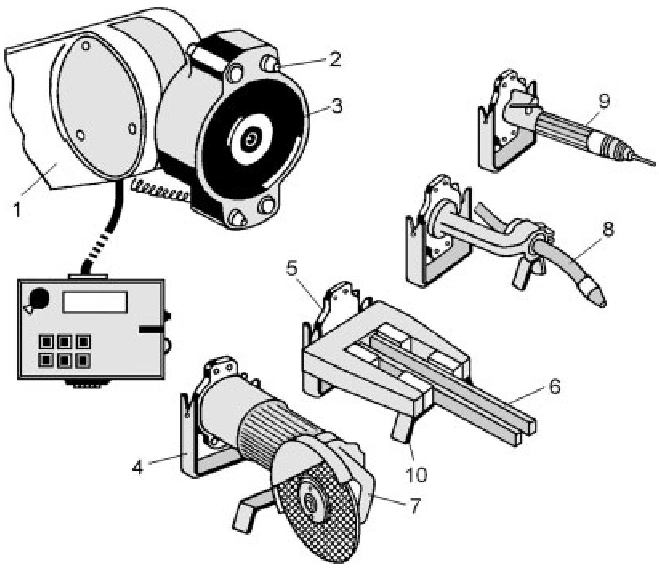


Fig. 12.28: Coupling elements gripper exchange systems
1 rotary control shaft, 2 tension screw, 3 magnetic field, 4 bayonet mechanics, 5 collet, 6 rotary ball slide, 7 cam slide against a roll, 8 cross pins against a radial groove, 9 pull and hold latch, 10 ball bearing, 11 hook connection, 12 spread roller mechanics

For example, the realization of the magnetic principle shown in Figure 12.28(3) results in an exchange system similar to the one presented in Figure 12.29. This is a somewhat older but still interesting exchange unit. It is possible to exchange tools, test instruments and grippers held in readiness in serial or disk magazines at the workcell periphery. However, the options for the coupling of signal, medium, and power lines are rather limited for this design and no longer satisfy modern industrial standards. Where the handling of machine tools is concerned, dynamic effects (of rotating mechanisms) must be taken into account and even vibration damping may be necessary. The use of electromagnetic holding force places additional demands on systems which must remain safe even in cases of power failure.



1 robot arm
2 locating and centring bolt
3 electromagnet
4 effector magazine
5 gripper flange
6 clamping gripper
7 motor tool
8 welding torch
9 drill spindle
10 magazine support

Fig. 12.29: Shape pairing effector exchange system (*ASEA*)

12.3.3
Joining Techniques and Process Media Connection

The coupling of a gripper with a handling machine can be realized in many different ways. Apart from manual and automatic exchange systems this can be achieved through:

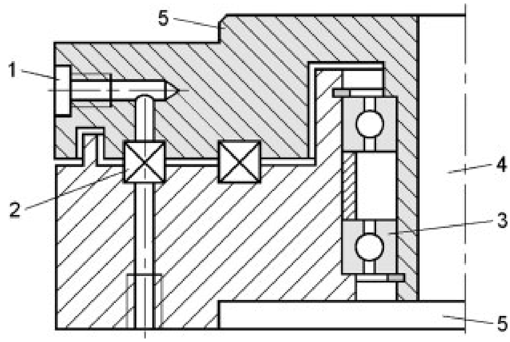
- Bolted joints in accordance with the appropriate standard (for example, DIN ISO 9409). Depending on the design, centring may be achieved using register pins, centring collars or centring sockets.
- Clamp connections with clamp rails or using a rounded shank clamp.

Depending on the dimensions of the gripper it may be necessary to include an adaptor plate. This plate has holes on one side according to the DIN-ISO flange norms (see Fig. 1.3) and on the other side the device specific geometry.

In addition to the mechanical robot flange connection provision must be made for electrical, pneumatic and (where necessary) hydraulic supply lines. For compressed air, ring shaped rotary lead-through glands may be used (Fig. 12.30). These can have several independent inlet and outlet channels.

The central hole is used for lines and cables. Either axial or radial connections may be used on both sides and rotation is not limited by stops. Nevertheless, the degree of rotation for cables and tubes located in the middle is normally limited to less than 360°.

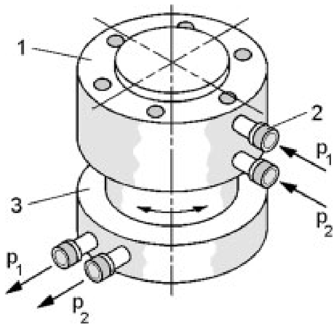
Lead through for electrical cables may also be integrated. Both power and signal lines may be included but for EMC reasons are normally separated by cable screening. General purpose non screened multicore wiring may be used in low power applications where voltages and currents are within 60 Volts and 1 Ampere respectively. Commutation of power and signal lines is possible but due to noise reasons is not recommended.



1 connection of process media
2 ring channel with special gasket
3 roller bearing
4 hollow central duct
5 centring collar

Fig. 12.30: Ring shaped rotary lead through

Figure 12.31 shows a standard rotary compressed air lead through suitable for unlimited rotation. More expensive designs include a larger number of feed-through channels.



1 ISO connection flange
2 compressed air line connection
3 flange

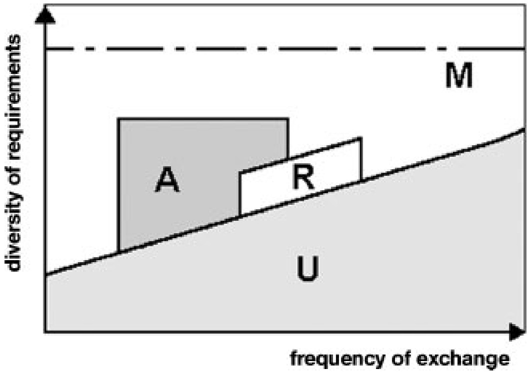
p pressure

Fig. 12.31: Rotary lead through for compressed air

12.3.4 Manual Exchange Systems

An automatic exchange system does not always offer the optimum solution in all situations. The frequency of exchange indicates the number of endeffectors which must be changed per unit time and the graph shown in Figure 12.32 shows applicability depending on task diversity and exchange frequency. A universal gripper normally possesses a large gripping range, gripping force control and flexible gripper jaws. As a rule this places demands on overall size and mass and can result in poor operational safety and higher costs. For this reason the employment of simpler grippers in conjunction with manual exchange is often an economic alternative. Automatic exchange may alleviate problems of size and weight but the cost factor remains, together with an additional time overhead compared to a universal gripper.

A very simple example of a rapid exchange system, often used in hand guided manipulators, can be seen in Figure 12.33. The coupling pilot, which uses an entry cone, is inserted into the upper part and pressed into the cross slide. On release of the slide the coupling



A automatic exchange systems
M manual exchange
R turret
U universal gripper

Fig. 12.32: Gripper exchange and requirement profile

pilot will be locked by spring forces. Lateral pins attached to the pilot prevent rotation of the gripper. Release is achieved by moving the cross slide to the left where the large central hole allows the gripper with the integrated coupling pilot to be extracted. However, this coupling is not suitable for endeffectors which must sustain large eccentric moments. The load hook, gripping hooks, liners, or self-made special grippers, as shown in Figure 12.33, must be equipped with such a coupling pilot (load capability typically up to 250 kg). Other designs for the upper part of the pilot coupling, in which locking is realized by cross pins also exist.

Catches along guide rails can also be used as mating elements between gripper and handling machine. Figure 12.34 shows one interesting design example.

Exact centring and retention of the gripper are performed by between different functional elements. Catch connectors are often made from heavy duty plastics which are considerably lighter (density of typical plastics is around 1.56 g/cm^3) than aluminium (2.8 g/cm^3). The catch connection can be released within seconds ensuring very rapid, low cost, manual gripper exchange.

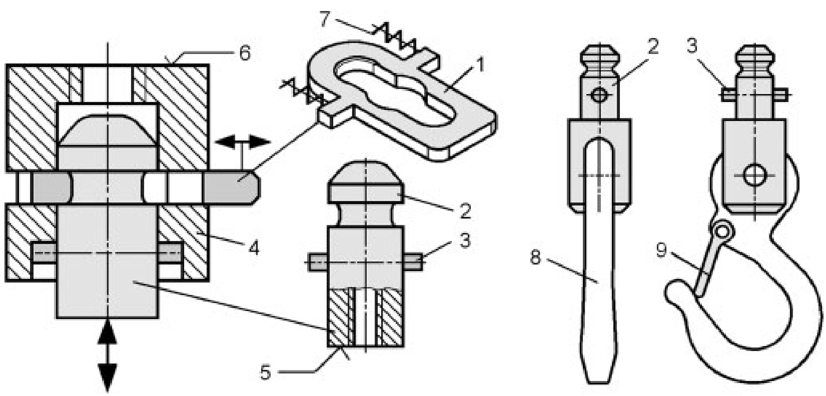


Fig. 12.33: Fast exchange coupling (*Landert*)
1 locking slide, 2 coupling pilot, 3 rotation protection, 4 carrier, 5 gripper connection M12, 6 manipulator / lifting tool connection, 7 retention spring, 8 load hook, 9 safety catch

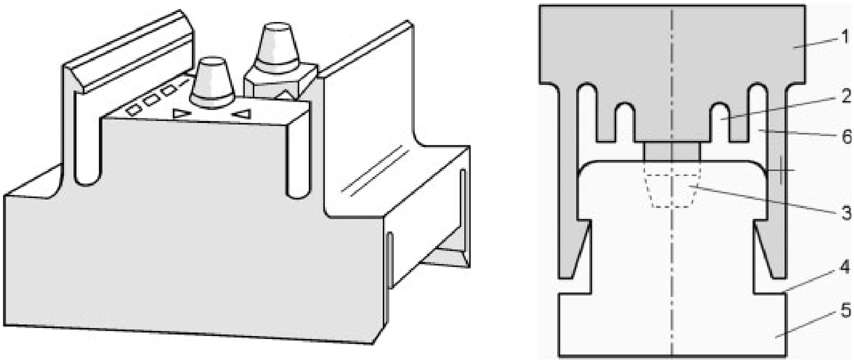


Fig. 12.34: Rapid gripper exchanger with catch element (*SCHUNK*)
1 catch connector, 2 power cable lead through channel, 3 centring bolt, 4 undercut, 5 gripper, 6 slot for dismounting tool

Two such exchange systems with a modular design are shown in Figure 12.35. The mating elements consist of round flanges manufactured from high-strength aluminium or C45 steel. However, as already mentioned, the combination of steel and aluminium elements should be avoided where possible and a metal to plastic interface is preferable. For the exchange systems shown, a hand operated shaft is rotated after mating, in order to lock the tool flange. If in addition power and information lines (sensors, control) are to be connected, one can use an extended version with additional couplings arranged at the periphery (Fig. 12.35 b). The design depicted in Figure 12.35 c makes use of a dovetail profile for mating and the two flanges are secured by a cross pin or locking bolt.

Figure 12.36 shows one further hand operated rapid exchange coupling used as the connection between a hand guided manipulator and an endeffector. Every endeffector must

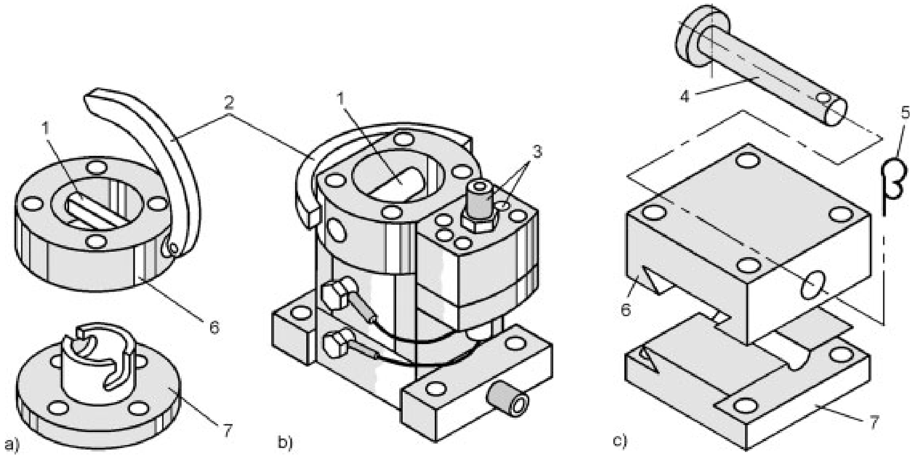
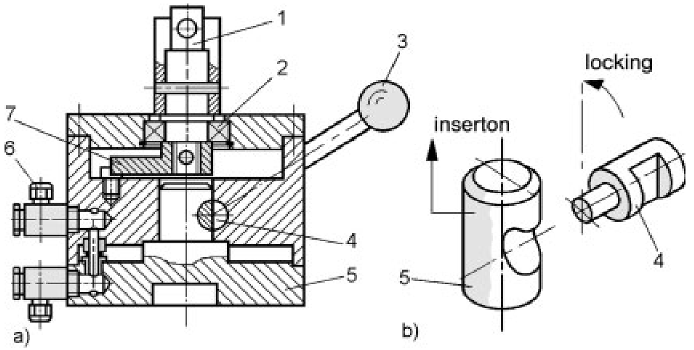


Fig. 12.35: Manual rapid exchange systems
a) mechanical coupling elements (*Grip* GmbH), b) multi-power coupling, c) dovetail coupling
1 shaft, 2 hand grip, 3 power and signal coupling elements, 4 locking bolt, 5 safety clip, 6 upper flange, 7 lower flange

be equipped with the lower coupling flange. Once the coupling of the two flanges has been achieved, a plug pin is locked through shape mating by appropriate pivoting of the hand lever. This exchange system contains an integrated coupler for compressed air. At the same time, the entire coupling is designed as a (hand force activated) rotation axis which is convenient and normal for applications with hand guided manipulators. However, multiple rotations are prevented by a stop.



1 coupling piece
2 ball bearing
3 hand stop lever
4 locking axis
5 gripper flange pin
6 air lead-through
7 rotation limiter

Fig. 12.36: Rapid gripper exchange

Bayonet nut connectors can also be used as couplings for rapid gripper exchange for which a low profile design is shown in Figure 12.37. A large entry cone supports rapid detection of the coupling centre. This design is also provided with a compressed air lead-through and additional coupling elements may be attached to the periphery. The locking hand lever is additionally secured by a latch to guard against unintentional release. This exchange system is also used primarily with hand guided manipulators.

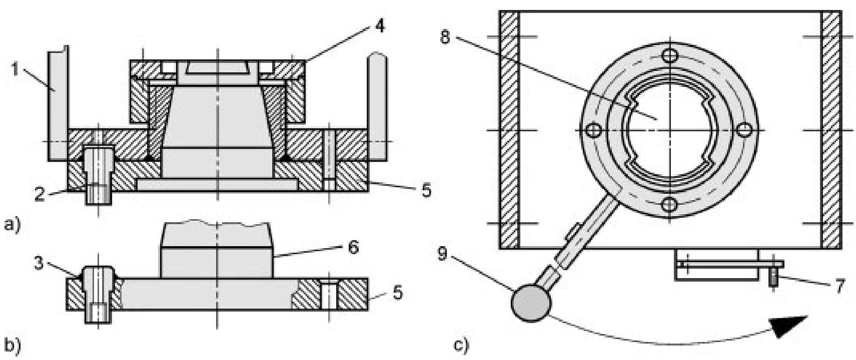


Fig. 12.37: Bayonet based rapid gripper exchange
a) cross section of clutched upper and lower flanges, b) design example for a gripper-sided lower flange, c) locking mechanism viewed from above
1 mounting, 2 compressed air coupling, 3 O-ring, 4 pivot segment, 5 coupling plate with conical acceptance, 6 mating cone, 7 latch locking, 8 locking profile, 9 pivot segment lever

12.3.5
Automatic Exchange Systems

Automatic gripper exchange led to something of a breakthrough in the industry. The essential advantage being the capability of not only gripper exchange but also a complete retooling (nut drivers, pneumatic hammers, drill spindles etc.) being possible. The insertion of an exchanger should not compromise overall accuracy and repeatability of the system. As illustrated in Figure 12.38, there are basically five functional principles involved.

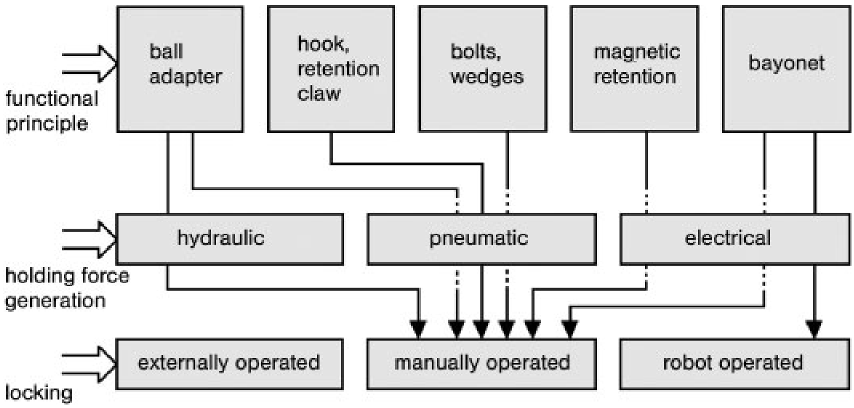
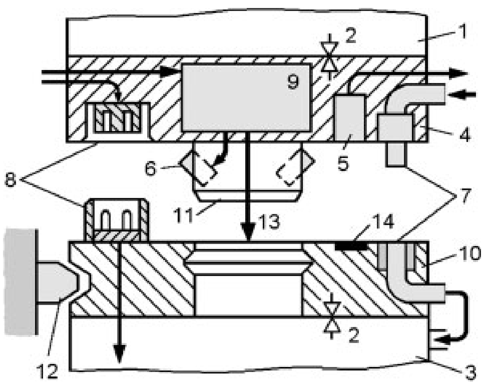


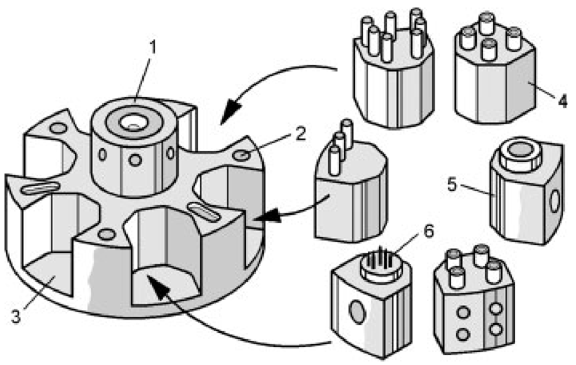
Fig. 12.38: Classification of exchange systems

The elements required for an exchange system are presented in simplified form in Figure 12.39. It is necessary to have an individual flange for each gripper. Details may differ in practical designs but in general the exchange systems are compact and their volume limited.



1 robot flange
2 interface
3 gripper
4 exchanger flange (robot)
5 proximity sensor
6 locking element
7 coupling elements (power and materials)
8 coupling elements (signals)
9 locking drive
10 exchanger flange (gripper)
11 mechanical coupling element
12 element for release of the gripper into the magazine
13 ejecting motion
14 code element

Fig. 12.39: Functional elements of an automatic exchange system



1 locking mechanics
2 search hole for cone bolts
3 exchanger flange (gripper)
4 compressed air coupling
5 fluid media transmitter (oil, water)
6 current, signal transmitter

Fig. 12.40: Modular design of exchange system (*Sommer-automatic*)

Proposals also exist for the modular design of separate coupling elements which can be installed into the coupling plates as desired. Such a system is schematically shown in Figure 12.40. However, the requirements for high accuracy are often better satisfied using compact exchange systems rather than through the use of modular components.

Simple manual gripper exchange makes sense only where the number of coupling connections to be realized within a given time is limited. If pneumatic, electrical power and signal lines must be simultaneously connected then an automatic exchanger is preferable. It has been demonstrated that it is possible to automatically connect and disconnect up to 28 lines, including power supply lines carrying up to 5 A. Resistance spot welding requires the transmission of up to 1500 A and, not surprisingly, such exchange systems can themselves have a mass of several kilograms resulting in a large moment of inertia. Mechanical connection after locking requires positional errors not exceeding 0.02 mm. Gripper exchange takes typically between 2 and 7 s depending on the size and mass of the gripper and the system.

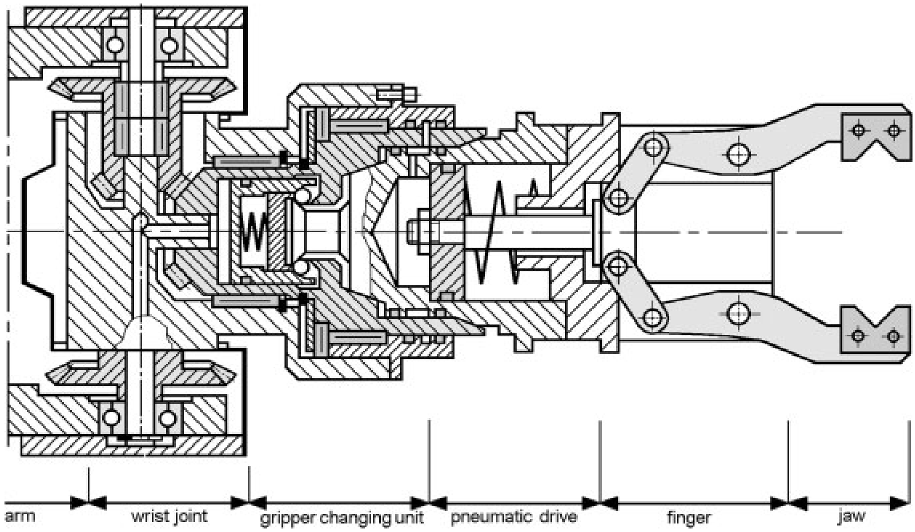
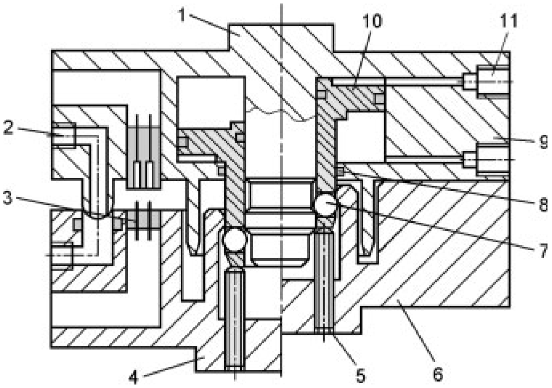


Fig. 12.41: Robot wrist with gripper exchange system and inserted gripper



1 connection flange
2 compressed air lead-through
3 electrical signal plug
4 exchanger flange (gripper)
5 stop screw
6 mobile carrier
7 ball
8 seal ring
9 fixed carrier
10 locking piston
11 compressed air connection

Fig. 12.42: Exchange system

The following examples relate to commercially available systems. Figure 12.41 shows a completely coupled system consisting of a robot wrist, exchange system and gripper. The hand can be rotated and pivoted. Both motions are induced by a bevel gear. The locking takes place mechanically and pneumatically using compressed air from the robot wrist. Closure of the gripper is also realized pneumatically and reopened with the help of spring force.

Figure 12.42 shows another exchange system which is also locked mechanically with the assistance of balls. In the course of coupling the piston is inserted into the mobile carrier (lower assembly unit) until it reaches the stop screw. On the application of compressed air to the piston, the ball ring moves over the centrally located mandrel taking the mobile carrier with it, thereby locking it against the fixed carrier. The presence of the balls then blocks the return of the mobile carrier. This state is preserved even in cases of pneumatic pressure failure.

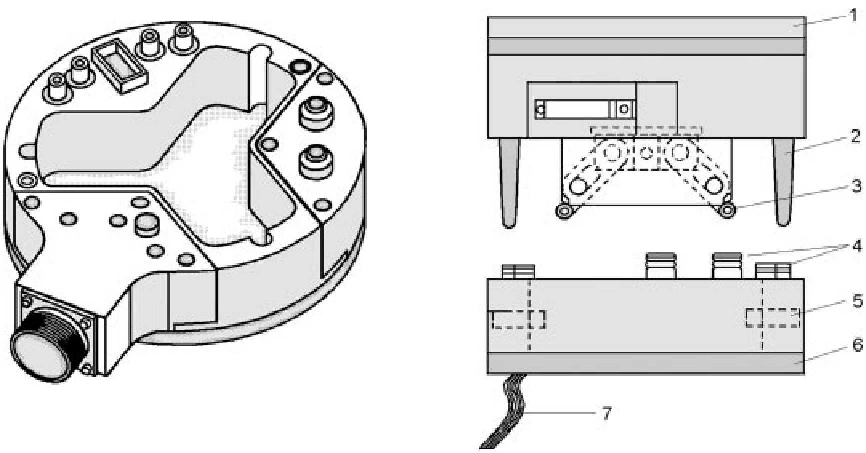


Fig. 12.43: Exchange system X Change (*Applied Robotics*, Schenectady, USA)
1 robot flange, 2 search and centring pins, 3 arm with locking roller, 4 compressed air coupling, electrical and signal lines, 5 open areas for the locking rollers, 6 gripper flange, 7 signal lines

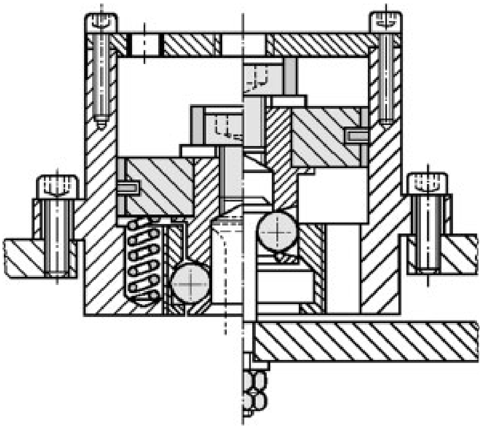
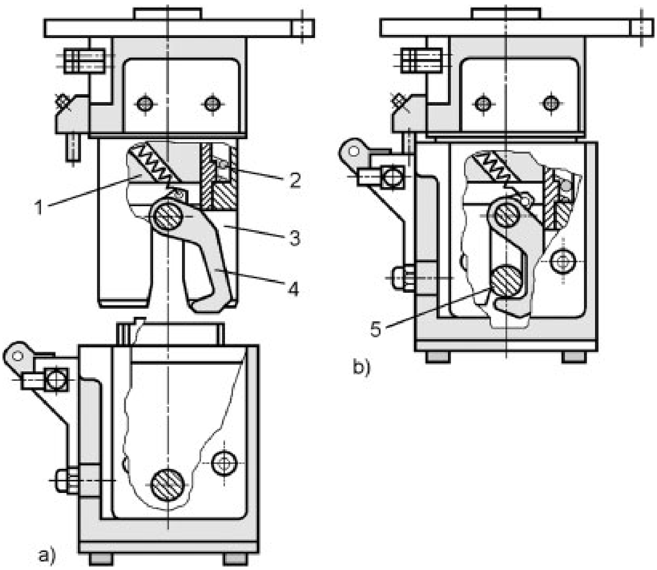


Fig. 12.44: Exchange unit for hand guided manipulators

For the exchange system presented in Figure 12.43 the arms with radially extending locking rollers are inserted into the gripper side of the flange during coupling. The connection is achieved through shape mating as in the ball locking example. The system is suitable for heavy grippers and tools and also contains integrated coupling elements for compressed air, high voltage, electrical power and signals.

Figure 12.44 illustrates another form of ball locking mechanism. Three balls placed in radially arranged conical recesses are pressed inwards along a curved trajectory as a result of spring clamping motion. Retention is achieved through shape mating behind the head of a clamp bolt and release is achieved by compressed air. The stiffness of the connection is somewhat limited but adequate for many applications such as hand guided manipulators.



1 pneumatic piston
2 return spring
3 lateral slot
4 locking hook
5 cross bolt

Fig. 12.45: Tool exchange system (*Fein*)
a) upper part released
b) lower part coupled

Another variation, presented in Figure 12.45, operates with a locking hook in a similar manner to large, multi-pole electrical plugs and sockets. Mating commences with pre-centring of the upper and lower parts at the insertion bevels. A locating pin takes over the exact positioning before the two parts are secured.

A down stroke of the piston leads to pivoting of the locking hook beneath the cross pin. This produces a secure connection of the upper and lower parts in accordance with the *Fail-Safe-Principle* (secure against consequential damage). The catch and locking hooks ensure full reliability even in cases of power supply failure.

12.3.6 Finger Exchange Systems

Because the resulting flexibility does not justify the complexity, the automatic exchange of gripper jaws or fingers is rarely used in practice. However, it can be an expedient alternative in many manual exchange cases. Consequently, gripper jaw designs employing several different profiles are not uncommon (Fig. 12.46). They are brought to the required position simply by rotation and locking.

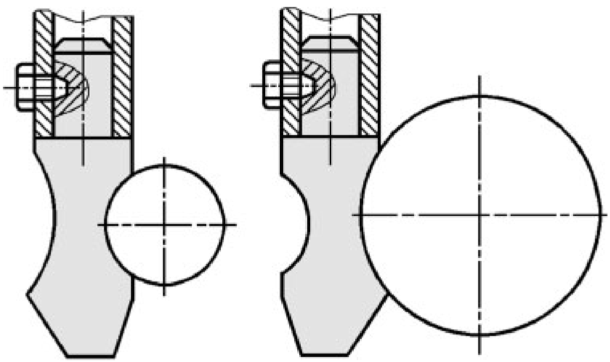
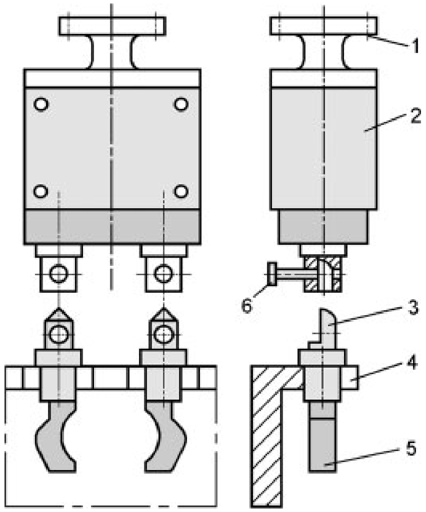


Fig. 12.46: Gripper jaw with two workpiece profiles

The configuration presented in Fig. 12.47 includes coupling elements between the gripper fingers and the basic gripper jaw thus making the gripper fingers together with the finger bearing an exchangeable unit.

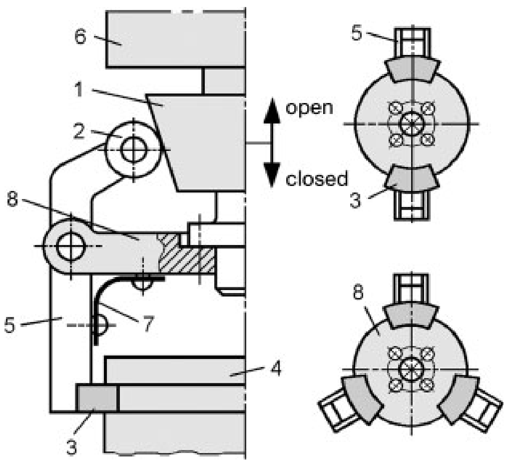
Finally, Figure 12.48 shows a design utilising a mechanical interface located between the gripper finger and the finger drive. The finger is driven by movement of a cone. The central location of the finger assembly and the roller-cone contact points are the only requirements for all such gripping units. These can be pivot fingers or parallel driven gripper jaws if the corresponding straight-line guides are provided.

In the few cases where the automatic exchange of gripper fingers has been implemented, it proceeds either in the form of a “flying exchange” or at a fixed exchange station. In most cases the entire jaw is replaced.



1 gripper flange
2 gripper
3 coupling elements
4 finger magazine
5 gripper finger
6 fastening bolt

Fig. 12.47: Principle scheme of a manual finger exchange system



1 cone piece
2 roller
3 gripper jaw
4 workpiece
5 finger
6 drive unit
7 leaf spring
8 base plate

Fig. 12.48: Gripping finger exchange (2 and 3 finger configurations)

12.4 Integrated Processing

In rare cases the operation of prehension is combined with a process such as crimping or welding. One such example is shown in Figure 12.49. The component parts are grasped one after the other by separately controlled grippers and subsequently assembled within the gripper. Where joining forces are small, pressing operations can be carried out within the gripper.

Figure 12.50 illustrates the assembling of a motor commutator with a gripper possessing integrated functions.

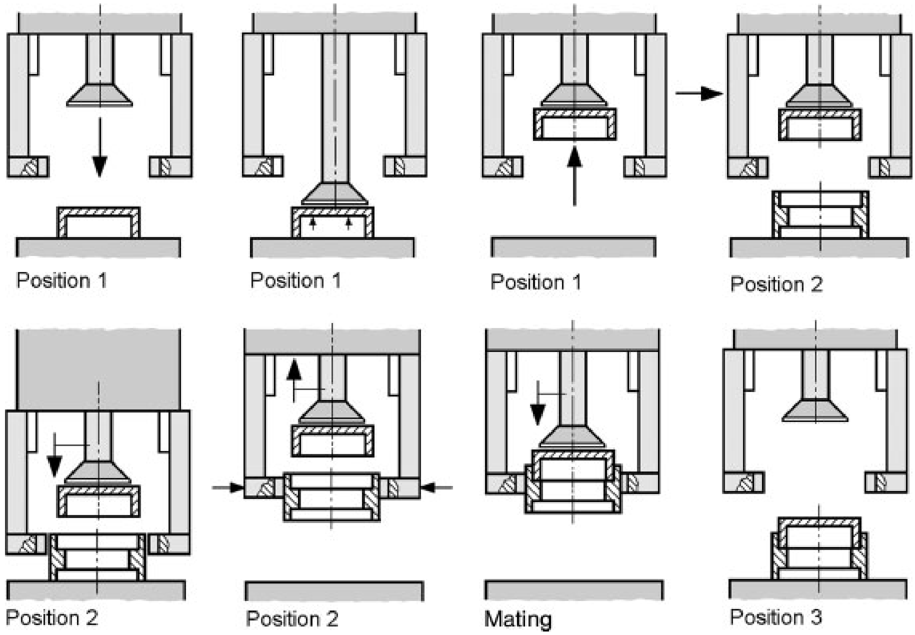


Fig. 12.49: Operational sequence for assembling two components in the gripper

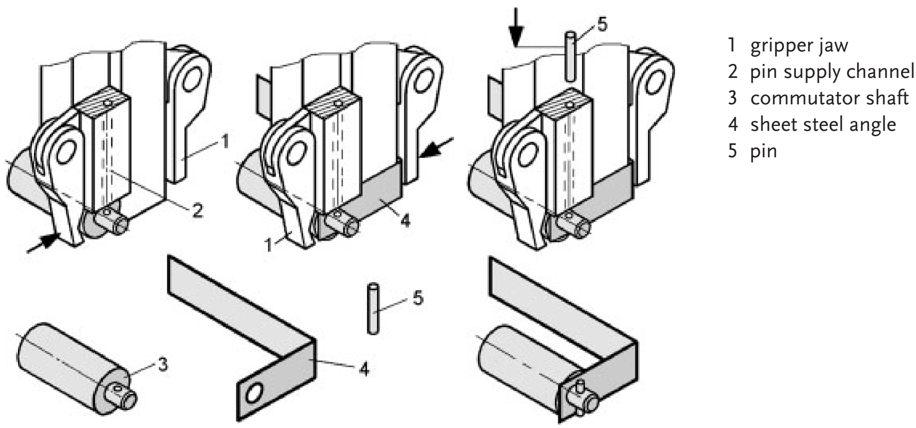


Fig. 12.50: Integrated assembling of a commutator shaft

Stable impactive prehension of the shaft allows the end of the shaft to be inserted into the hole in the sheet steel angle plate. The assembly operation is completed with downward motion of the gripper which forces the securing pin into the small hole in the end of the shaft. Finally, the complete sub-assembly is deposited into a magazine.

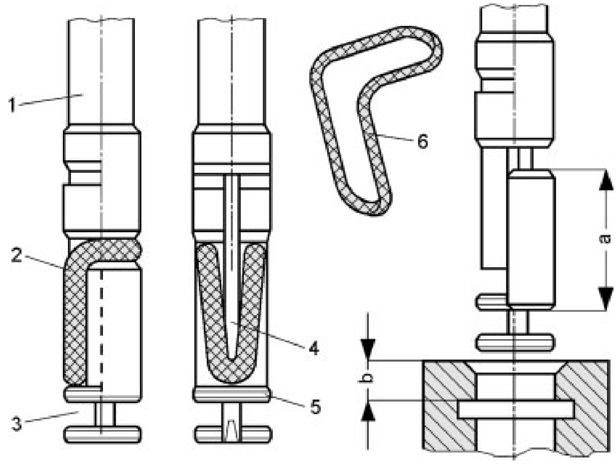


Fig. 12.51: L-shape gripper for mounting of O-rings
1 active element, 2 O-ring clamped into L-shape, 3 collet for the positioning of the ring at slot depth *b*, 4 hook, 5 semicircular disk, 6 L-shaped O-ring
a separation depending on the ring size

The mounting of O-rings used for the sealing of machine parts are another special case of integrated processing. It is not trivial to place the easily deformable O-ring inside a hole or recess because its diameter is obviously slightly larger than the diameter of the recipient. Let us consider for this purpose the gripper shown in Figure 12.51 which simultaneously serves as a joining tool [12-4]. The acquired O-ring is temporarily distorted into an L-shape within the gripper. The gripper is then inserted into the workpiece to a depth *b*. The elasticity of the L-shape leads to its relaxation in the slot.

Many other forms of integrated processing of flexible parts, too numerous to be described here, are practiced in industry. For further reading Chapter 14 may be of interest, and particularly Section 14.7.2.

13
Compliance

Even in an ideal world where parts are machined to a very close tolerance and assembly systems operate with absolute accuracy and repeatability, there will always be some difficulty in the mating of parts due to inhomogeneities of surface characteristics, effects of contaminants such as oil, moisture resulting from humidity etc. In the real world these problems are further exacerbated by the lack of consistency between parts and machine characteristics. When parts are assembled manually the human operator compensates for small differences in component dimensions by a combination of intelligence, based largely on past experience, and the physical dexterity offered by the fingers. This latter criterion is further augmented by the closed loop control provided by the link between the senses and the brain. Furthermore, though we are not always conscious of the fact, most manual assembly operations rely on a high degree of mechanical compliance in the fingers. For example, when one screws a nut onto a bolt it is not usual to align the two precisely by sight before threading is commenced. We are more likely to offer the nut to the bolt in roughly the correct position before orientating by feel whilst allowing the fingers to comply with the more dominant orientation forces which become apparent as the threads mesh. Meanwhile, the dynamic decision making capability provided by the human control structure allows problems of misfit or cross-threading to be avoided or resolved. This concept of compliance is of even greater importance where automated systems, lacking the degree of sensory intelligent control taken for granted in the human model, are to be used for the continuous handling of parts of uncertainly defined dimension. A good example is the handling of soft fruit in agricultural automation. The compressibility of air can be helpful here in that the pneumatic actuators used to drive the jaws of an impactive design can also provide the necessary compliance needed to avoid damage. Pneumatic systems can also be made to provide a large degree of mechanical variation in order to accommodate a range of object sizes [13-1].

According to Mason, compliance is the tendency of a body to move due to the internal effects of the forces applied to it, for example bending and twisting, play in the joints between sections of the body, or between it and another body [13-2]. Furthermore, compliance may be split into two basic types: *passive* and *active* [10-2]. A good example of passive compliance is a simple metal spring. Using this analogy, active compliance could be achieved if the spring coefficient were controllable. The theories behind compliance have much in common with those applicable to motion damping. Consequently the methods and technologies used are often very similar.

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

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The mating of parts must satisfy specific operating conditions resulting in the following types of compliance according to their respective principle of operation:

- Uncontrolled (passive) mating mechanisms: *remote centre (of) compliance* (RCC) *mechanism*.
- Controlled (active) mating mechanisms: *instrumented remote centre (of) compliance* (IRCC) *mechanism*.
- Combined (active and passive) mating mechanisms.

Furthermore, torque resistant mechanisms: *near collet compliance* (NCC) are required when, e.g., it is necessary to turn a screw.

RCC link
Flexible multi axis gripper suspension with decoupled degrees of freedom for compensation of small angle and lateral offset errors in mating operations [13-3] in which an object can be pivoted about a "virtual" centre which is situated outside the gripper.

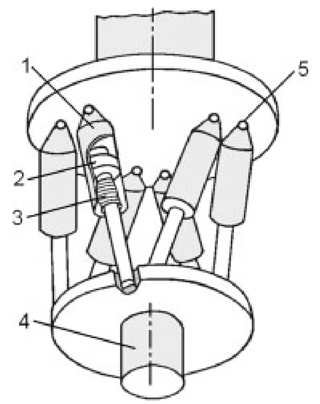
13.1 Remote Centre Compliance (RCC)

The precise mating of tightly fitting parts often necessitates the physical modification of the components in question. Rather than making the robot more accurate, a reduction in the overall accuracy requirement often provides a more cost effective solution. Countersunk holes and chamfered shaft tips are good examples of "design for automation". A further requirement is that the gripper must be capable of accommodating these deliberately introduced tolerances. Consequently, the use of controlled, or at least predictable, compliance can be most helpful. One device which offers this possibility, deliberately introduced to robotics to avoid the need for extensive sensing and data processing, is the passive compliant mechanism known as the Remote Centre Compliance, or RCC [11-7]. Nevertheless, the addition of instrumentation, such as force sensing, can also help facilitate error recovery strategies helpful in detecting mismatch and preventing jamming.

Figure 13.1 shows an early solution, developed at the Draper Laboratories, for an RCC which exhibits 6 degrees of freedom. It is suitable for the insertion of short bolts (diameter 12 to 58 mm, length 25 to 100 mm) where mechanical play may range from 12 to 24 μm. It has been demonstrated that it is possible to compensate for lateral errors as large as 2 mm and angle errors along the axes of insertion as large as 2.5°.

The RCC is constructed in such a way that there are separate structural elements for the position and angle deviations. In the case of angle error compensation the assembly part moves about a virtual centre of rotation which is located in the middle of the lower front surface of the workpiece. Angle error compensation and position error compensation are decoupled and take place independently of one another [13-4].

Figure 13.2 shows the principle and function of each component in a simplified RCC. The compliance function is a typical mechanical second order model comprising a mass (gripper and workpiece), a spring force and a damper as illustrated in Figure 13.1. The



1 damper cylinder
2 damper piston
3 return spring
4 gripper flange
5 ball joint

Fig. 13.1: Passively operating compensation system from *McCallion* (1980)

springs may be of metal or elastomer construction [13-5]. Elastomer links are designed as rubber-metal composites with a definite axial hardness and shear resistance. Many design examples for RCC units have been published in the literature [13-6] and extensive information can be found elsewhere [13-7].

The orientation motions enforced by the force field resulting from contact between the robot and gripper flanges are directly related to forces exerted vertically.

Figure 13.3 shows the effect of placing a peg directly into a chamfered hole. The peg initially makes a single point contact and the RCC takes up any horizontal movement as the peg is pushed vertically downwards into the hole. Figure 13.3 b illustrates the effect of tilting the workpiece (or the gripper) to achieve a two point contact between the peg and the hole. The RCC in this case makes a slight angular displacement possible. For an extremely

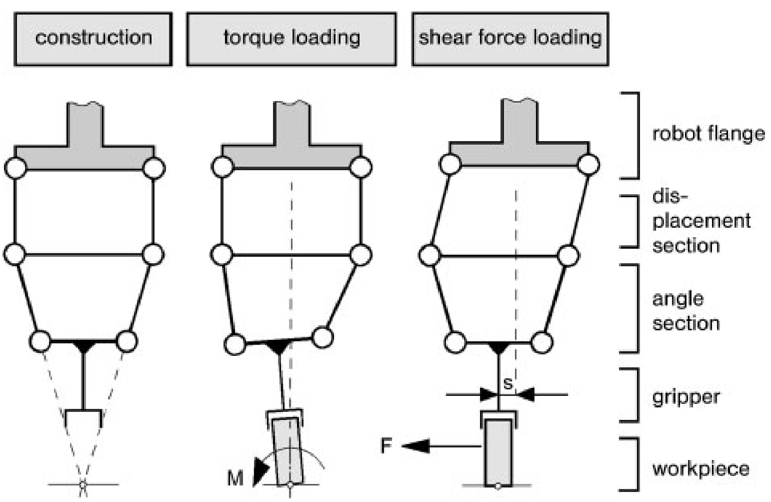
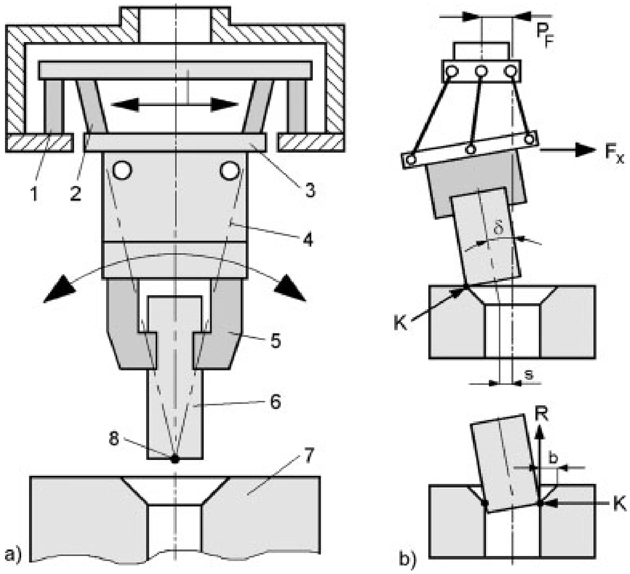


Fig. 13.2: Principle and function of an RCC
M torque, *s* displacement path, *F* force



1 elastomer spring for position error compensation
2 spring for angular error compensation
3 flange plate
4 gripper
5 gripper finger
6 workpiece
7 workpiece recipient
8 ideal axis of rotation

F mating force
b chamfer width
s position displacement
δ inclination error

K contact force
R friction
F_x unguided reaction force for position correction
P_F positioning error

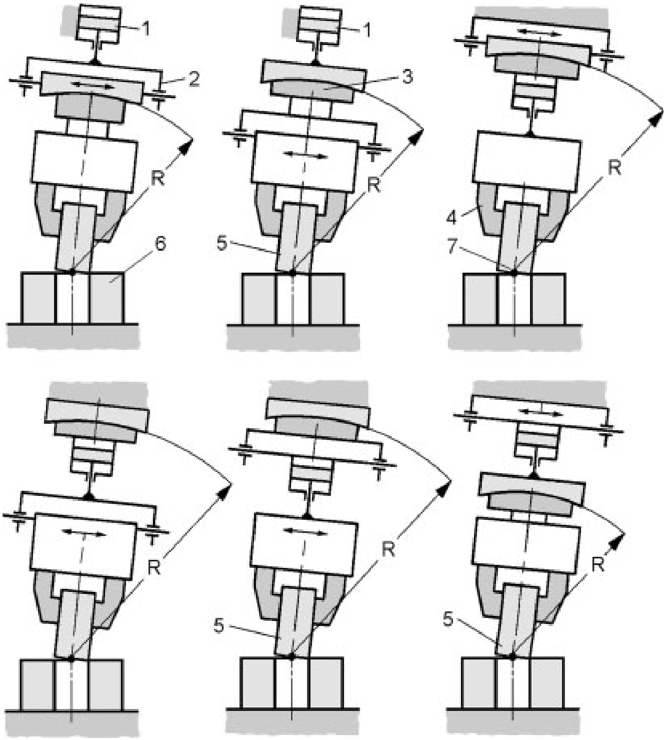
Fig. 13.3: Operational principle of an RCC
a) task, b) principle of passive position correction

readable analysis of this, and related situations, the work by McKerrow is strongly recommended [10-2].

Compensation motions proceed in two phases:
- Compensation of the position deviation (*s*) during the sliding of the workpiece along the chamfer of the workpiece recipient (single point contact).
- Compensation of the position deviation *δ* during insertion of the workpiece into the workpiece recipient (two point contact) through rotation about the ideal axis (8).

Mating mechanisms are specified according to the following important parameters:
- Overall size and mass.
- Maximum position and angle deviations between the assembly parts.
- Maximum applicable mating force.
- Overload protection.
- Complexity of fabrication and respective costs.

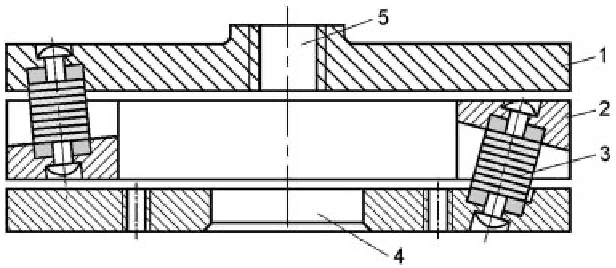
The art of designing RCC links consists in locating the apparent centre of rotation at the end of the workpiece. This leads to an effective pulling of the workpiece into the hole. In alternative designs, the pneumatic damper may also be used as an additional actuator as shown schematically in Figure 13.4. Though in practical applications motion is the role of the robot, motion in the Z-axis (direction of insertion) may be augmented by a pneumatic cylinder [13-8].



1 joining force generator
2 position compensation, slide axis
3 angle compensation
4 gripper jaws
5 workpiece
6 workpiece recipient
7 apparent centre of rotation

R radius

Fig. 13.4: Operation of RCC employing two shear and one swivel joints

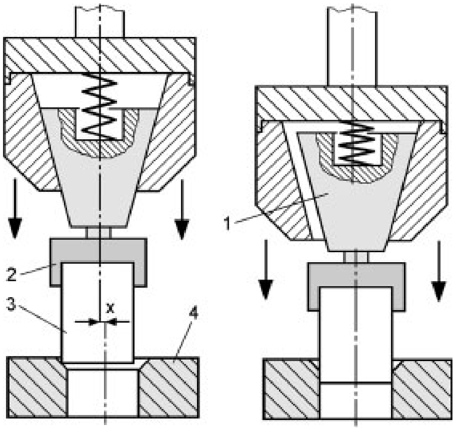


1 robot flange
2 intermediate ring
3 spring
4 gripper flange
5 robot flange connection

Fig. 13.5: Design of a standard flat RCC mechanism

It is essential for the RCC link to be designed as flat as possible in order to save space, as shown in the example in Figure 13.5. The use of metal springs allows the transmission of larger forces in the Z-axis than is possible with elastomer springs [13-5].

The special design shown in Figure 13.6 uses two cones, one inside the other. Initially, the workpiece makes contact with the chamfer. However, since the joining head continues its downward motion, the inner cone which is subjected to spring retaining forces is allowed to move. This introduces a small degree of mechanical play allowing the inner cone to make contact with one of the inner surfaces of the hollow outer cone. This compensates for axial deviations χ making mating of workpiece and recipient possible.



1 cone with 15° inclination
2 gripper
3 workpiece
4 workpiece recipient

x axis displacement

Fig. 13.6: Double cone RCC

The designs of RCC hitherto considered are simple, light and effective as long as positional and angular deviations are not too great. However, unexpected forces such as jamming due to burrs in a hole are often beyond the abilities of an RCC. An extension to this simple passive compliance is the Instrumented RCC or IRCC.

13.2 Instrumented Remote Centre Compliance (IRCC)

Unlike the purely passive RCC systems, IRCC links actively compensate for angle and lateral displacements. The compensation error is measured, for example using a PSD, and corrections are performed actively. Figure 13.7 shows one solution where such a device is inserted between the gripper and robot arm. Rough alignment is realized actively while fine positioning is ensured passively by means of the usual elastic elements. The PSD used in Figure 13.7 is a four quadrant photodetector. Gripper dislocations lead to displace-

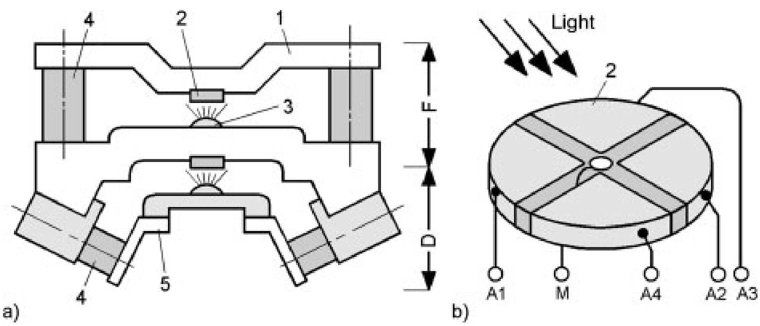
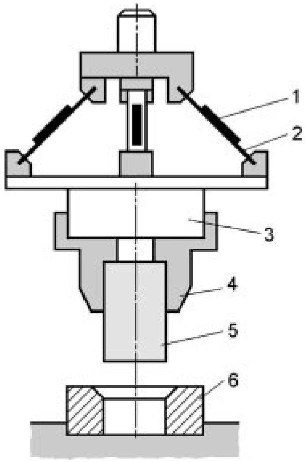


Fig. 13.7: Principle of an IRCC link
a) optical sensor compensation system, b) PSD (position sensitive detector),
1 robot flange, 2 PSD, 3 LED, 4 elastomeric element, 5 gripper flange
A photodetector connections, *D* moment compensation, *F* force compensation, *M* mass connection



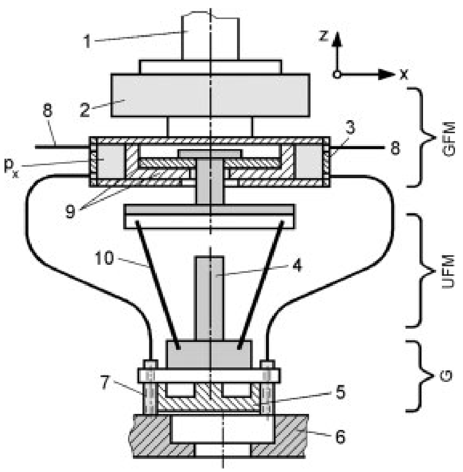
1 strain gauge
2 leaf spring
3 gripper
4 gripper jaw
5 workpiece
6 workpiece recipient

Fig. 13.8: IRCC system using force measurement

ment of the LED and hence to differential photocurrents between PSD segments. These differences are measured and the results used for robotic position correction.

The compensation mechanism schematically shown in Figure 13.8 contains leaf springs as elastic elements. Deformation of these springs can be detected using strain gauges and the information used for position correction of the gripper.

Figure 13.9 shows a hybrid mating mechanism consisting of both passive and active systems. The actively controlled part operates pneumatically in the x and y directions. Two dynamic pressure nozzles (sensors) are used to measure distances from the base flange. The pneumatic control equipment, which is directly coupled with the sensors, consists of air suspended displaceable plates. The displacement continues until all sensor orifices attain the same position relative to the base hole sides and the measured pressure differences in the control chambers vanish. This signals the conclusion of the mating process.



1 gripper guide gear
2 rotary unit
3 linear slide element
4 pneumatic cylinder for mating motion
5 assembly part
6 base
7 sensor (dynamic pressure nozzle)
8 compressed air connection
9 air-suspended plates
10 spring elements

ARCC active RCC mechanism
PRCC passive RCC mechanism
G gripper

Fig. 13.9: Combined joining mechanism with pneumatic sensors and steel spring elements [8-1]

13.3 Near Collet Compliance (NCC)

Compensation mechanisms are also required when mounting threaded components and turning screws. As a rule the RCC elements cannot be used for this purpose because they are not torsion proof and consequently the transmitted torque is insufficient. However, this task can be fulfilled by metal concertina like spring bellows (Fig. 13.10) employed for passive mating.

These are referred to as NCC links (NCC = near collet compliance) where typical concertina sheets are around 0.2 mm thick [13-9]. A metal concertina mating mechanism as the one shown in Figure 13.10 is characterized by zero backlash, simple construction and small mass.

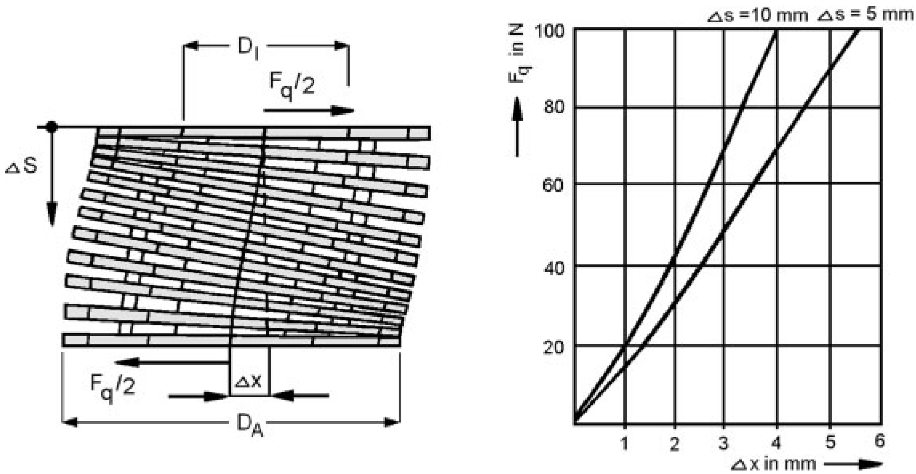


Fig. 13.10: Torsion proof compensation mechanism (bellows element and force-path diagram) D_A outer diameter, D_I inner diameter, F_q shear force, Δ_s superimposed axial prestressing, Δ_x lateral displacement

As a consequence of its design the NCC element locks into only one of six possible degrees of freedom, namely rotation about its longitudinal axis. Consider the process of attempting to accurately mesh threads while turning a screw. During a possible search sequence, three translations and rotations about two axes together with forced rotation about the third axis is necessary. From this it clearly follows that, when using a NCC element, the screw can perform a five-axis search motion. Typical rotation search time for locating and engaging a screw in a threaded hole amounts to less than a second.

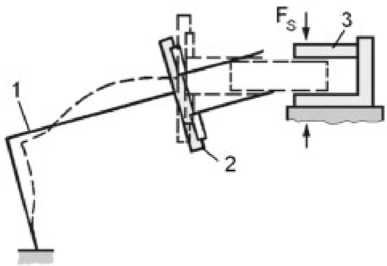
Similar to the RCC links, the elasticity of the metal concertina allows compensation of position deviations between the two assembly parts. For screw mating a rotation of half a nominal screw diameter (half turn) should be adequate for thread meshing.

An axial pre-tensioning (pressing) of the metal concertina makes it possible to modify the stiffness in the x- and y-directions. This means that different mating tasks may be performed using the same NCC mechanism. NCC devices are available in different dimensions, multi-layered and with different torsion resistances.

Some of the advantages of the NCC elements over conventional RCC links can be summarized as follows:
- Mass is reduced by as much as a factor of 50 in comparison with RCC links.
- Integrated elasticity in the direction of the screw fastening; no screw-nut springing necessary.
- No uncontrolled changes in spatial position of screw and nut assembly tools in non-perpendicular screwing operations as a result of own mass.
- Torsion angle to tightening angle ratio during tightening operations is better than 1 : 30.

13.4 Parts Feeding

The feeding of parts directly into retaining devices (such as clamps) as illustrated in Figure 13.11 can lead to a force conflict situation in cases where the workpiece is still held by the gripper and simultaneously clamped in the retaining device. In such cases it is advantageous to have a degree of compliance (such as an elastic interface) between the robot wrist and gripper.



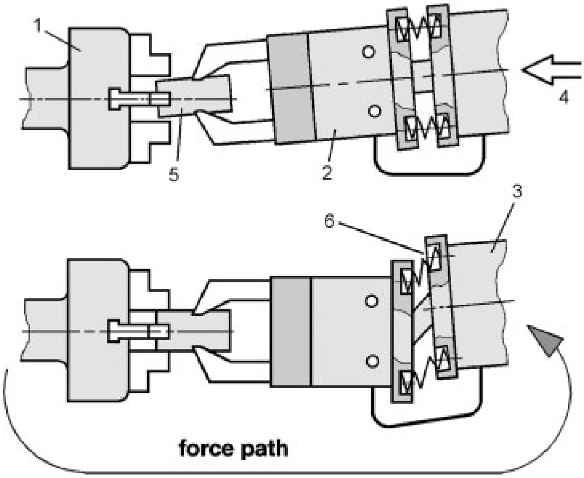
1 handling equipment
2 gripper
3 clamping device
F_S clamping force

Fig. 13.11: Force conflict when loading a clamping device

Failure to include such compliance can lead to overload of the robot joints and the gripper finger guideways. Figure 13.12 shows a simple example of design and usage of such simple spring loaded RCCs.

In some cases it is necessary to press the workpiece home (to the end stop in the retainer). So much the better if this can be done without driving the robot further after object release.

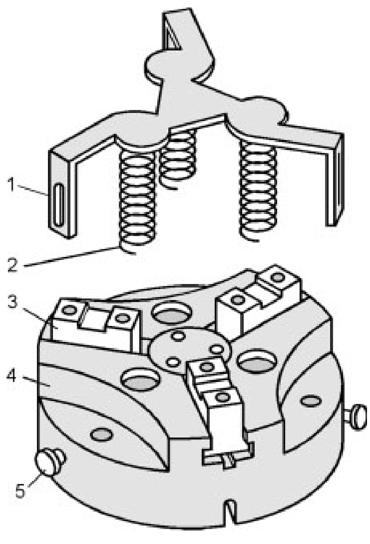
Once the gripper jaw is opened, a spring loaded star pushes the workpiece against the stop surface in the retainer. Retention of the springs (Fig. 13.13) is maintained while the object is gripped. The spring ejection force comes in to play at the point of object release. Depending on the overall size of the gripper, the ejection forces lie typically between 20 and 420 N with travel ranges from 3 to 12 mm. Needless to say, the reactive forces occurring at the point of release must not exceed the capabilities of the manipulator.



1 chuck
2 gripper
3 moving unit
4 direction of motion
5 workpiece
6 balancing unit (a standard component used as a force-free unit)

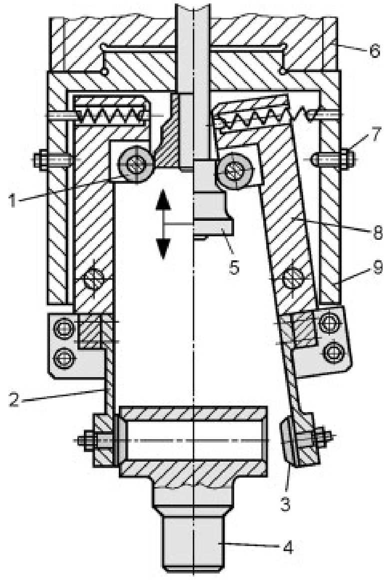
Fig. 13.12: Gripper with an RCC

The special requirement of providing two different holding forces occasionally occurs in assembly operations such as the “peg in hole” task. Initially, the part to be mounted must be “softly” grasped until successful insertion is achieved. Thereafter it must be grasped firmly as the object is pushed home. One such gripper, capable of performing these operations in a purely mechanical manner, is depicted in Figure 13.14. Since the fingers are designed as flat springs, two different gripping forces occur as a result of the spring constant.



1 spring loaded star
2 ejection spring
3 basic jaw
4 gripper housing
5 ejector retention

Fig. 13.13: Three finger gripper with a star-shaped ejector unit (*PHD Inc.*)



1 curve roll
2 exchangeable gripper finger
3 exchangeable gripper jaw
4 mounting part
5 driving curve with 3 settings
6 pneumatic cylinder connector
7 stop screw
8 pivot finger
9 gripper housing

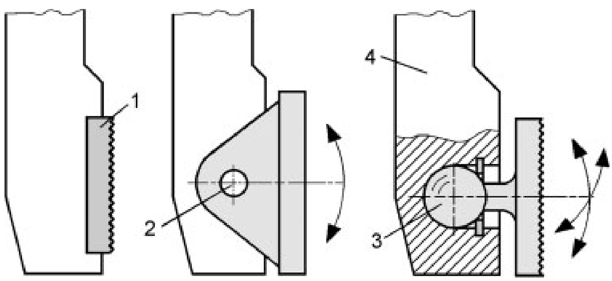
Fig. 13.14: Variable force assembly gripper

13.5 Mechanical Compliance

Many possibilities for the design of flexible gripper jaws exist. These include:
- Elastic jaw coatings.
- Pendulum jaws (with one or more pendulum axes).
- Shape-adaptive and shape-preserving jaws.

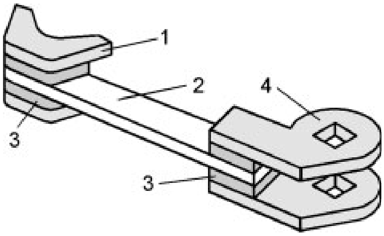
Some often used solutions are depicted in Figure 13.15. The hardness of the elastomeric coating should be selected according to the prehension task in question. Such coatings increase the coefficient of friction and hence contribute to prehension reliability.

The gripper finger with extended jaw shown in Figure 13.16 is produced as a rubber-metal composite. This compensates for deviations from the specified object size. This is of special importance for grippers with uncompensated actuation, e.g. a cam disk instead of a pneumatic piston. The spring hardness of the rubber body depends on the hardness of



1 elastomeric coating
2 axis
3 ball joint
4 gripper finger

Fig. 13.15: Flexible gripper jaws

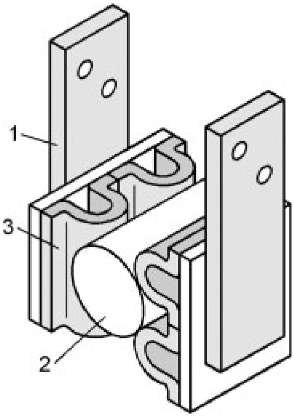


1 gripper jaw
2 gripper finger
3 vulcanized rubber layer
4 attachment to the angular gripper

Fig. 13.16: Gripper finger with elastic properties

the chosen rubber material. Such grippers are used, e.g., in rotating bottle cleaning machines.

The jaw pair shown in Figure 13.17 allows prehension of cylindrical objects lying on a planar surface. Centring is achieved in a similar manner to that of prismatic jaws.



1 gripper finger
2 workpiece
3 rubber adaptor

Fig. 13.17: Elastomeric gripper jaw pair

Industrial requirements for increasing flexibility in manufacturing place enormous demands on gripper designs to be compatible with different workpiece shapes. A lot of technical proposals exist but few of them are feasible for real manufacturing applications. Figure 13.18 presents a classification of these possibilities.

Gripper jaws with several prehension points relating to the object make the gripper a "multi-point gripper". Such grippers with up to 9 prehension points, used for mounting of

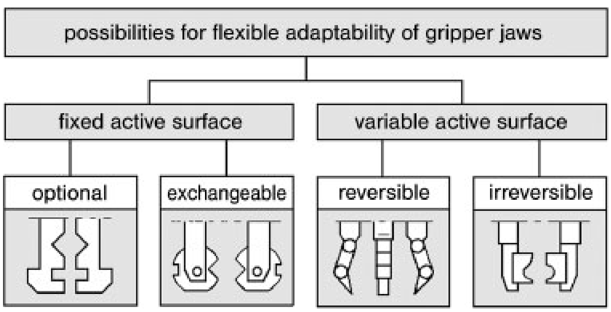
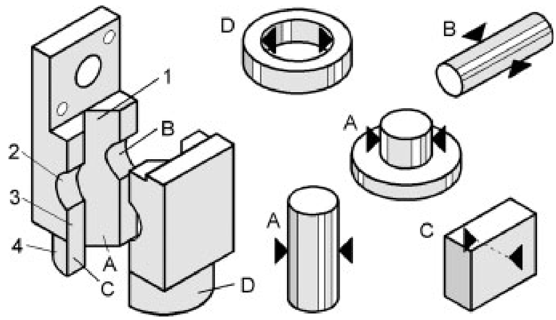


Fig. 13.18: Classification of shape-adaptable gripper jaws

gear assemblies, have already been described. Although such grippers are flexible in the specific mounting cycle, they are simply components in a single purpose automation process. The prehension points on the gripping surfaces are used with a degree of deliberate redundancy and exchange of the gripper is not normally necessary.

Sometimes it is possible to design the gripper jaws in such a way that they are capable of handling several parts of differing shape. A simple example is shown in Figure 13.19. The vertical prism A allows the prehension of vertically orientated cylindrical parts while the horizontal profile B is suitable for horizontally orientated rods. The flat surface C is also useful and the contour D is adapted for internal prehension, e.g. for the handling of toroidal profiles. This avoids the necessity of gripper exchange within the assembly facility. Nevertheless, these are special purpose jaws. Examples of exchangeable fingers and gripper jaws were presented in Chapter 12.



1 prism
2 round surface
3 flat jaw
4 shaped element for internal grip

Fig. 13.19: Multifunctional gripper jaw and examples of matching workpieces

The next large group of flexibly adaptable grippers employ conformable surfaces. These may be "locked" once a given profile has been adopted, as shown in Figure 13.20 [13-10]. This procedure has two steps:

- Sampling of the contour.
- Fixing of the contour with force closure (locking).

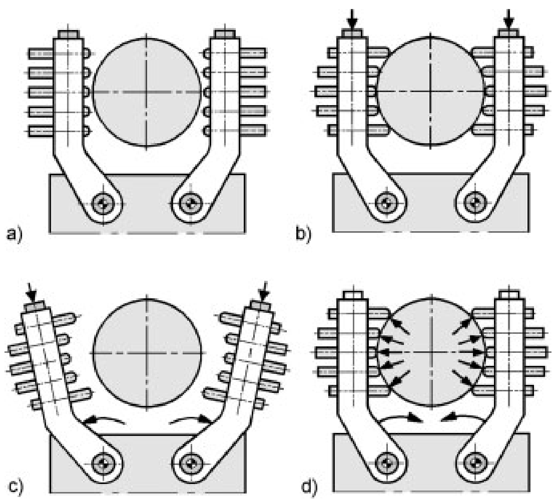


Fig. 13.20: Gripper with shape adaption
a) initial situation
b) shape adoption
c) shape saving
d) object prehension

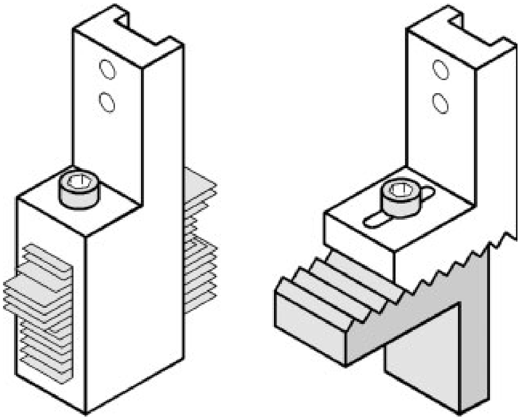


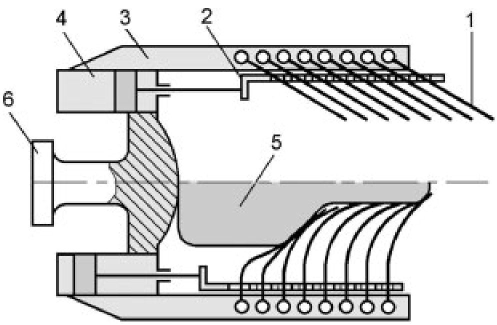
Fig. 13.21: Adjustable gripper jaws

Although the basic principle of shape-adoption is simple, like the omnigripper previously described, its mechanical realization required a large number of moving parts. Consequently such grippers are rarely implemented in real industrial applications.

The gripper jaws shown in Figure 13.21 are more realistic in this sense. The steel lamellae are displaced against each other and then secured. The serrated surfaces allow slip-free mounting and ease of adjustment.

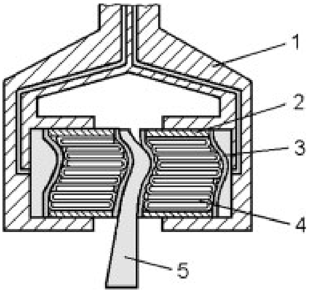
The following grippers are provided with reversible shape conformation which takes place anew for every gripping cycle. The idea illustrated in Figure 13.22 demonstrates a gripper, the fingers of which are built with plastic lamellae. When gripping, these lamellae are pulled towards the object adopting its surface topology. The functional principle of this laboratory model is reminiscent of bringing together the palms of the hands. Its concept is intended for service robots in the acquisition of a range of household tools.

The gripper jaws applied to an irregular shaped workpiece in Figure 13.23 are in principle elastic but can still effectively transmit force because their interior is stabilized by steel tape and the motion resembles that of a pneumatic piston. Each jaw is a separate hermetically sealed block. The cover surfaces are made from vulcanized rubber. The large object contact area reduces the surface pressure which is advantageous when handling sensitive (e.g. wooden) parts.



1 spring steel or plastic lamella
2 slide
3 arm
4 compressed air cylinder
5 workpiece or tool
6 connecting flange

Fig. 13.22: Lamellae gripper (Karlsruhe University)

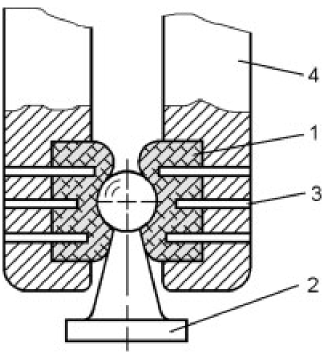


1 carrier with jaw guide
2 gripper jaw
3 elastic cover surface
4 wound steel tape
5 workpiece

Fig. 13.23: Gripper with multi-link jaws (Russian Patent B 25 J 15/00 626 947).

There are also a large range of more exotic ideas for gripper jaws, e.g. bags filled with powder. The jaw shape can be stabilized and hardened by the application of vacuum in a similarly manner to vacuum-packing.

Gripper jaws which can adopt the shape only once are called irreversible. The jaw shaping elements are made from plastic materials like (soft) silicon rubber mastic or modelling clays. The shape adoption is realized manually by casting, dispersing or foaming. Some materials harden alone and others require chemical or thermal post treatment. Figure 13.24 shows an example. Larger jaws are additionally stabilized by core pins. This method of shape adoption is efficient and especially applicable to the prehension of spherically shaped objects.



1 plastic bulk material
2 workpiece
3 core pin

Fig. 13.24: Shape-adopting gripper jaw

The addition of coatings to gripping surfaces in order to increase friction can also be used to provide a degree of compliance and even shape adaptation. There exist elastomeric mats which may be secured, by means of glue or plastic pegs into corresponding hole arrays, onto the gripper surface. One such example is shown in Figure 13.25.

For the handling of hot workpieces the contact surfaces can be additionally enhanced with Duran glass (SiC-fibre reinforced Duran glass). The theoretical maximum working temperature is 1200 °C, the limit of resistance in bending is 900 MPa and the density is 2.5 g/cm^3.

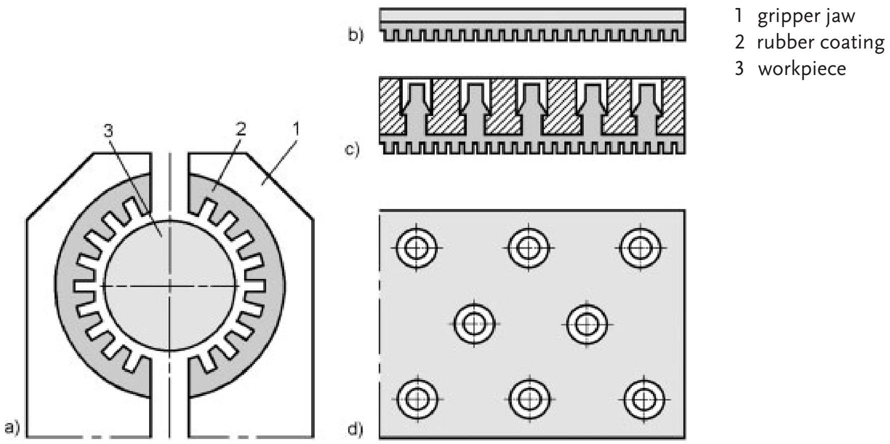


Fig. 13.25: Rubber knob bar as a gripper jaw coating
a) coating for round parts, b) adhesive coated bar, c) pegged bar, d) jaw surface

Hardened overlay plates or machine steel screws with knurled, grooved or corrugated surfaces are also a solution (Fig. 13.26) for less delicate tasks. This ensures stable holding of the part even in the presence of large turning moments, e.g., when handling large steel sheet parts requiring forces of up to 30,000 N. Needless to say, localised surface damage is very likely and consequently this method is not suitable to all automation tasks.

Special jaws may also be designed to perform a function in addition to simple prehension. Figure 13.27 shows one such example where the insertion of integrated circuit pins into corresponding bore holes requires that each pin be simultaneously bent to the correct angle.

The profiled jaws tend to bend the component pins to the correct angle for insertion, afterwhich precise positioning is essential. Nevertheless, for larger integrated circuits having 24 pins and more, a degree of dextrous manipulation is needed to ensure correct insertion of all pins. This problem, more than any other, is what forced the industry to change to surface mount device (SMD) technology. Consequently, this method is somewhat obsolete and will not be discussed further here.

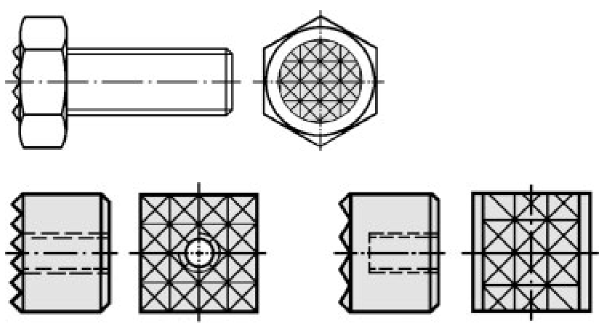


Fig. 13.26: Gripper jaw screw and clamping tip attachments

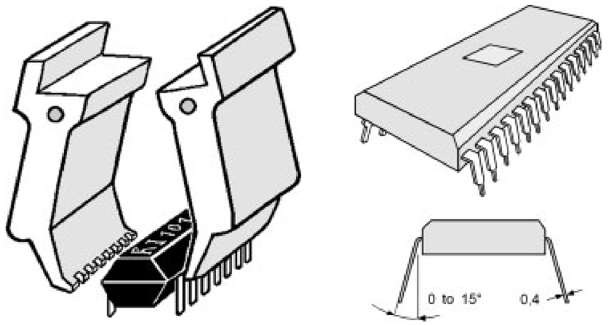
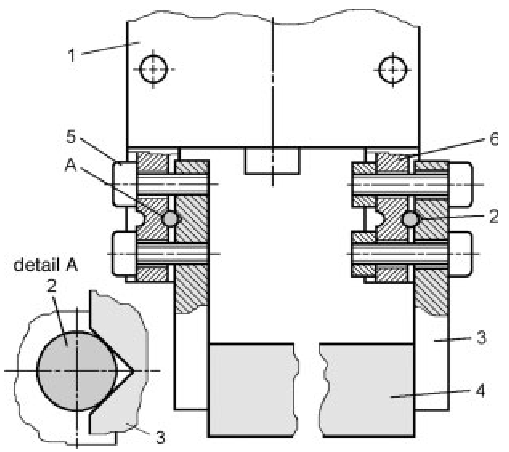


Fig. 13.27: Prehension of integrated circuits.
Left: gripper jaw construction for the given electronic component
Right: pins delivered with 15° angle

The attachments to gripper jaws can also exhibit some special features. Figure 13.28 shows how a gripper jaw can be adjusted to the gripper finger. As a result, the prehension force of the toggle lever gripper depends largely on the travel of the jaws. Which is why, as can be seen in Figure 13.28, the gripper finger is retained against a hardened pin. Adjustment of the two fixing bolts makes it possible to move the point at which the build up of prehension force commences.



1 gripper
2 roller bearing (hardened pin)
3 gripper jaw
4 workpiece
5 clamping screw
6 gripper finger

Fig. 13.28: Adjustment possibilities for gripper jaws

13.6 Pneumatic Compliance

A large degree of compliance may be avaialble in cases where prehension is achieved through the expansion of an elastic membrane or cell against the surfaces of an object. Often the pneumatic pressure required is only slightly above ambient air pressure. Ambient air pressure is nominally 1 Bar and conversion to other systems can be carried out with help of the following data.

Conversion of pressure units:
1 bar = 10^5 Pa
1 bar = 100 000 N/m^2
1 bar = 14.5 psi (= lbf/in^2)
1 bar = 750.062 Torr (mm Hg)
1 bar = 1.0197 Atmospheres

13.6.1
Internal Prehension Through Membrane Expansion

Internal grippers hold the workpiece with the help of elements which are expanded following insertion into the hole or cavity within the object to be prehended. Purely mechanical versions of this impactive internal prehension have already been discussed in section 3.2.4 of Chapter 3. Alternatively, these can consist of protrusions on a rubber membrane which are attached to a metal carrier as shown in Figure 13.29. The prehension range is small because the expansion range of the knobs is small. Operation outside of a cavity should be avoided because overexpansion of the membrane in the absence of a counterforce may cause damage.

Such grippers consists of only a few components and the extending protrusions ensure large frictional coefficients resulting in substantial retention forces. This gripper is particularly suitable for insertion into smoothly finished holes. The following table presents a selection of standard installation sizes:

Mandrel diameter D [mm]	Max. (internal) span diameter [mm]	Protrusion extend force [N]	Mandrel length [mm]	Mass [kg]
15.0	17.5	100	42	0.03
34.5	39	300	56	0.12
70.5	81	1500	92	0.67
119.5	135.5	3500	145	1.2

The specifications for the holding force are given for a full working pressure of 6 bar. The reproducibility amounts to 0.2 mm because the outward motion of the protrusions is not synchronized.

The gripper shown in Figure 13.30 consists of a hexagonal carrier with built-in pressure elements. When compressed air is supplied this results in a membrane stroke of about 3 mm and return of the membranes is provided through the elasticity of the membrane material.

Compressed air bags in the form of strips are also used for internal prehension, e.g. for the lifting of tubes as can be seen in Figure 13.31. The bags are attached to an internal carrier and their inflation leads to contact and retention of the object through frictional forces. The most commonly used materials for such bags are:

- Polyamide tissue
- Polyamide/Polyester
- Nylon cord

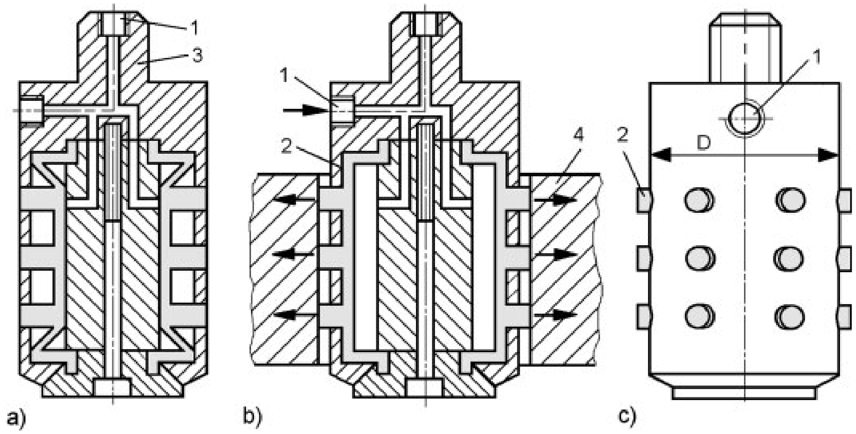
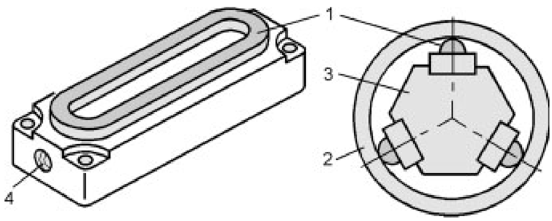


Fig. 13.29: Internal gripper (*Sommer-automatic*)
a) relaxed state, b) energized state, c) external view with extended protrusions
1 compressed air connection, 2 rubber roll, 3 aluminium housing, 4 prehended object



1 pressure element (*Festo*)
2 workpiece
3 gripper carrier
4 compressed air connection

Fig. 13.30: Internal gripper based on pressure elements

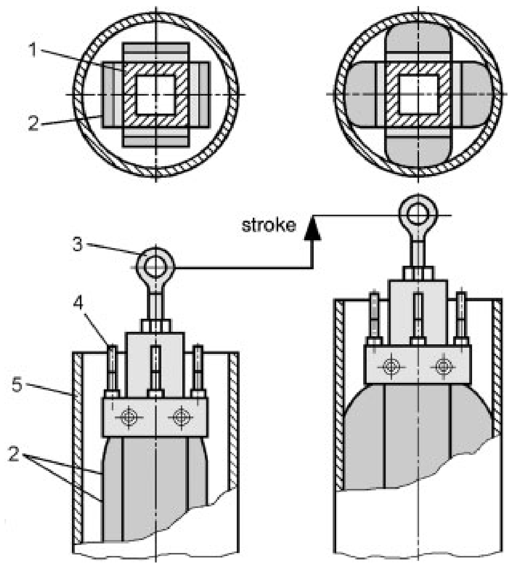
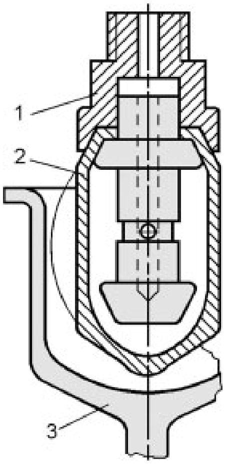


Fig. 13.31: Internal gripper based on compressed air bags (*STIITS*)
1 internal carrier, 2 compressed air bag capable of working under pressure up to 7 bar, 3 lifting lug, 4 compressed air connection, 5 gripped object, e.g. stoneware tubes for wastewater



1 carrier
2 rubber bag
3 object

Fig. 13.32: Pneumatic internal gripper (*FIPA*)

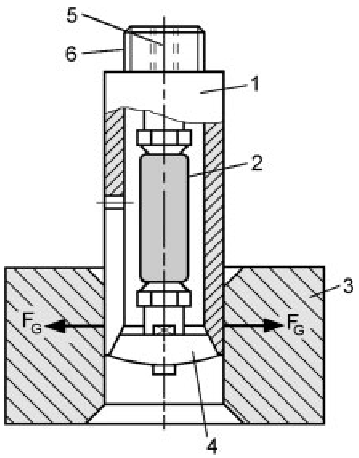
These types of gripper are found in industrial applications such as chain or steel wire hoists and hand guided manipulators.

The classical design of an internal gripper possessing an inflatable bag is shown in Figure 13.32. The maximum pressure of the compressed air supply should not exceed 2 bar. Such gripping technology is used e.g. for the handling of hollow glass or plastic components. The usable prehension diameter range depends on the overall size of the task but it is somewhat larger than that illustrated in Figure 13.29. Typical technical dimensions are given in the following table:

Connection thread	Grip diameter in mm	Total length in mm
M10	17 to 25	101
M12	27 to 40	120
M16	37 to 50	120
M20	47 to 65	128

The next example shows an internal gripper consisting of an external collet chuck which is driven by a fluid muscle. Although the segments of the collet chuck act as an "intermediate gear" (material joint structure), the solution is rather simple and the resulting prehension forces can be enormous (Fig. 13.33).

The workpiece prehension force F_G is produced by a cone activated by the fluid muscle. The cone slope prevents self-blocking because the elastic force of the multiple slit collet chuck is used as a restoring force. The stroke of the muscle can be quite small (in most cases between 0.2 and 0.3 mm) but the forces developed can be relatively high.



1 collet chuck
2 fluid muscle
3 workpiece
4 cone
5 compressed air supply
6 threaded shaft

F_G gripping force

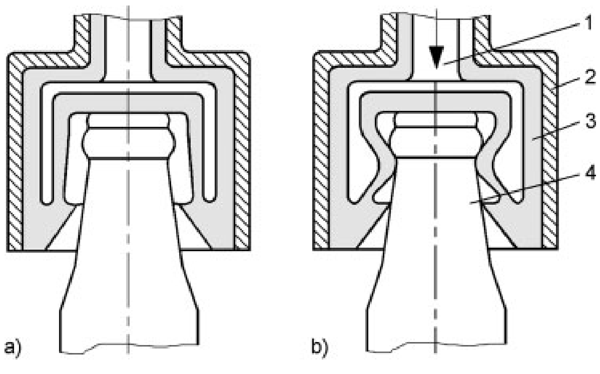
Fig. 13.33: Internal gripper based on collet chuck principle

13.6.2 External Prehension Through Membrane Expansion

External prehension through membrane expansion is well suited to workpieces having round and well accessible parts. The expansion of the membrane adapts to the profile of the object as is presented in the examples shown in Figures 13.34 and 13.35.

Typical candidates for prehension with this type of gripper are cylindrical profiles such as bottle necks. The bottle gripper depicted in Figure 13.34 utilizes the shape matching of the pressurized rubber membrane for prehension. The shaped inset is externally supported by the surrounding metal sleeve.

The gripper shown in Figure 13.35 consists of a frame with built-in pressure elements driven from a compressed air supply of 6 bar. When pressure is applied these rubber elements produce a stroke of about 3 to 5 mm (depending on the installation size). A metal plate can be secured to the rubber upper surface in order to reduce the wear of the rubber bag through abrasion (see also Figures 13.30 and 13.40).



1 compressed air
2 metal housing
3 shaped rubber inset
4 bottleneck

Fig. 13.34: Bottle gripper
a) relaxed state
b) energized state

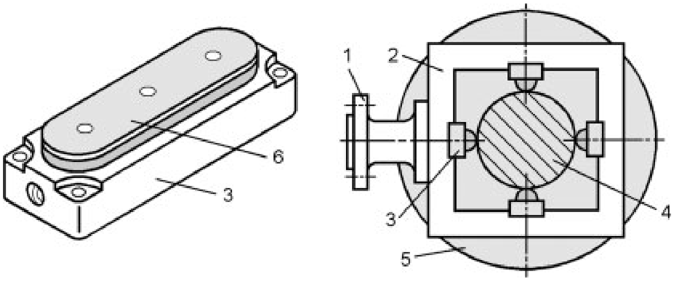


Fig. 13.35: Internal gripper based on pneumatic pressure elements
Right: top view. Left: pressure element

Tubular grippers may be used for cylindrical and slightly conical parts, for example Figure 13.36.

The same principle applies to the method depicted in Figure 13.37. The compressed air bags tolerate neither sharp edges, debris nor jagged contact surfaces. The gripper shown in Figure 13.37 a contains a built-in bar codereader making content specifications and other information for each package available for control purposes.

One further interesting solution for a bottle gripper, though not restricted to this field alone, is depicted in Figure 13.38. The strip shaped compressed air bags serve as impactive prehension elements. The unpressurized bags are lowered by the gripper between the bottle necks of multiple bottle rows. When pressure is applied prehension is achieved as the bags expand against the bottle necks.

Two further examples are shown in Figure 13.39. In the first case, the compliant prehension of delicate workpieces is realized by a rubber bellows under pressure. However, the

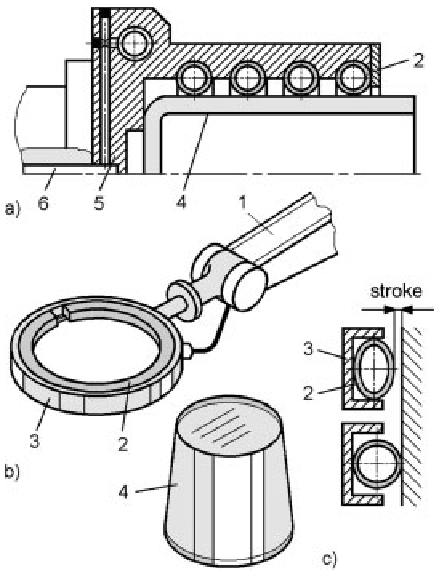


Fig. 13.36: Tube based gripper designs
a) gripping of round parts [13-11]
b) shrink collar gripper [13-12]
c) clamping procedure

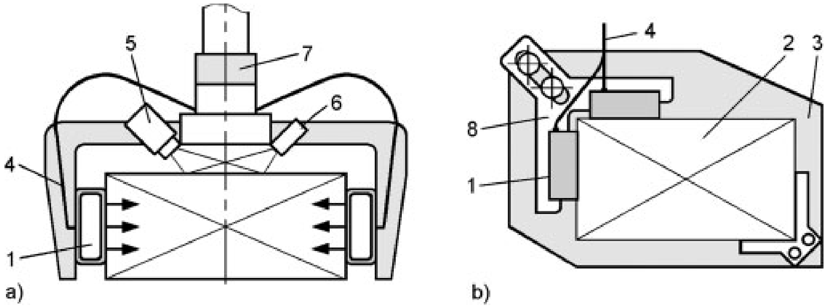
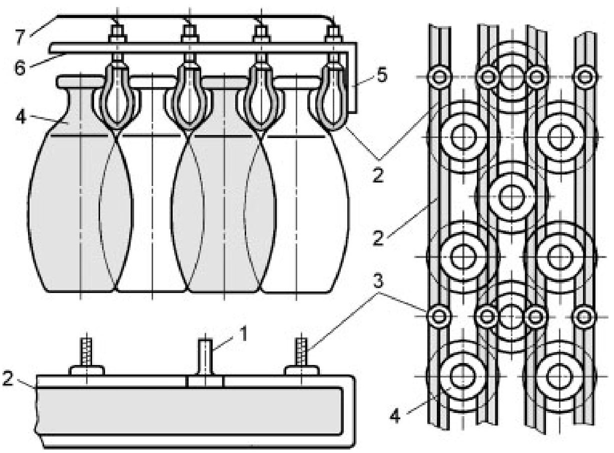
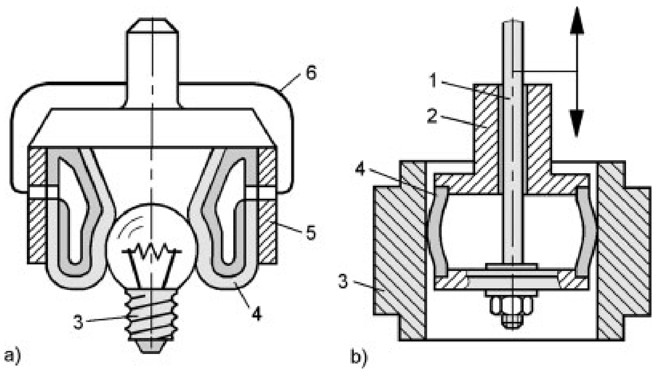


Fig. 13.37: Impactive prehension with a compressed air bag (*Pronal*)
a) design principle, b) size adjustment, 1 bag, 2 gripped object, 3 frame, 4 compressed air line, 5 camera (bar code reader), 6 illumination, 7 swivel, 8 adjustable angle



1 compressed air connections
2 strip shaped compressed air bags
3 threaded securing elements
4 gripped object (bottle)
5 limiting constraint
6 gripper base plate
7 compressed air line

Fig. 13.38: Bottle gripper (*Pronal*, France)



1 pull rod
2 housing and guide
3 workpiece
4 rubber cylinder
5 cladding cylinder
6 compressed air line

Fig. 13.39: Gripper with flexible shaped elements
a) prehension of delicate shaped parts, b) internal membrane gripper

positioning accuracy of such grippers is not very high. This also holds true for the gripper depicted in Figure 13.39 b in which a pull rod causes bulging of the rubber cylinder leading to prehension of the workpiece.

The clamping modules depicted in Figure 13.40 (as already mentioned) can also be used as active gripper elements. They are quite simple and the pre-stressed membrane automatically resets itself. The object contact area can be enhanced by using a metal plate to protect the delicate rubber from wear, although the membrane is normally made from polyurethane which is pretty durable. However, since the response time of these elements is very short and there is no protective limit for full stroke, "empty" gripping should be avoided. Typical performance characteristics are given in the following table:

Pressure membrane area in mm	**Stroke in mm**	**Clamping force for a stroke of 1 mm**
3 × 16	3	95 N
4,9 × 50	4	350 N
9,5 × 161	5	1690 N

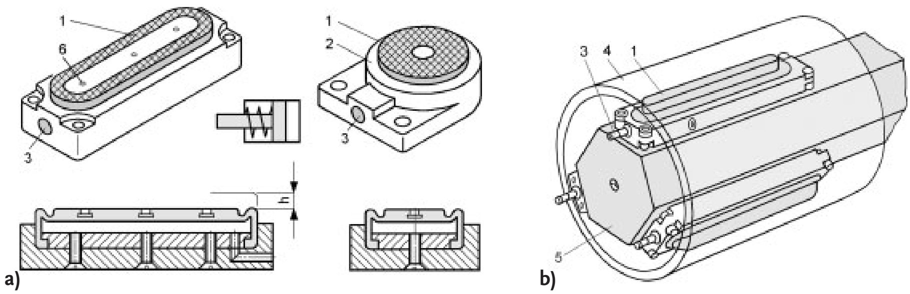


Fig. 13.40: Prehension module (*Festo*)
a) module, b) internal gripper
1 membrane, 2 housing, 3 compressed air connection, 4 gripped object, 5 gripping mandrel, 6 borings for protective plate attachment, *h* clamping stroke

It is often necessary to include a degree of compliance specifically to allow for deviations in object size rather than for protection of the objects surface. The example shown in Figure 13.41 provides firm impactive prehension without giving any consideration to surface damage whilst at the same time the closure of the gripper fingers is limited through compliant elastomeric mechanisms at the finger joints. Such grippers are ideally suited to the handling of objects with relatively large tolerances such as wine bottles.

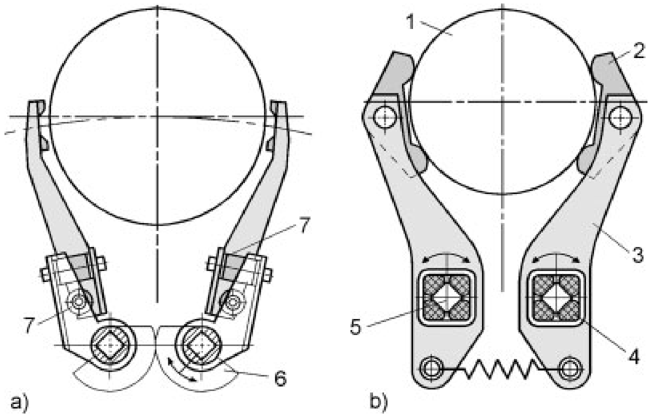


Fig. 13.41: Gripper with compliance integrated with the finger joints
a) compliance through rubber torsion elements, b) compliance through rubber bushes
(German Patent DE 29712066)

13.7 Shape Adaptive Grippers

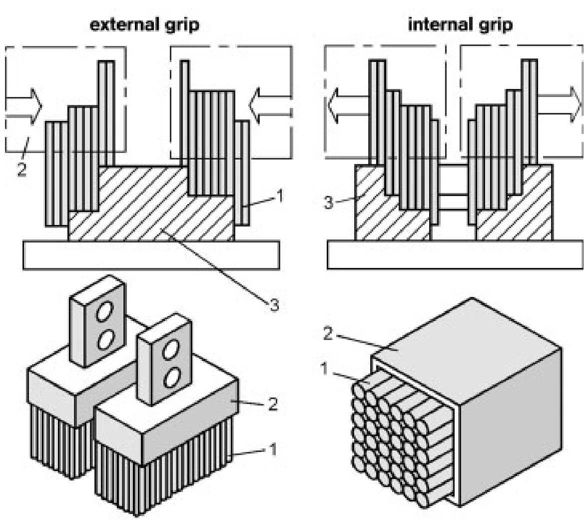
The handling of irregular and/or unpredictably shaped objects places demands on gripper flexibility which extend beyond that normally solved by multiple gripping head or exchange systems. Grippers operating with pin arrays or pin packages are technically interesting but rarely used in practice. Many variations and prototypes are known from the technical literature, one example being the omnigripper [13-13].

13.7.1 Partially Compliant Shape Adaptive Grippers

The omnigripper (Latin *omnis* meaning "all") is a conformable gripper developed in the UK, the two jaws of which consist of densely packed, solid pins (Fig. 13.42) which are allowed to move longitudinally and independently. When the jaws make contact with an object the pins corresponding to the shape of the object are displaced before clamping takes place. With this method it is possible to handle parts having very different shapes (even conical) and sizes, by both internal and external prehension. Moreover, the displacement of the pins yields a three-dimensional image of the object.

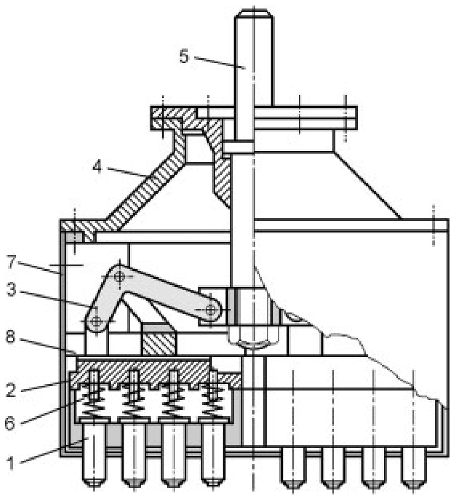
Figure 13.43 shows a modified version of the omnigripper. When formed around the object, the two gripper jaws close concentrically. Only a relatively small jaw travel of around 10 mm is needed. The redundant pins descend against a stop which, like the central travel rod, is not shown in Figure 13.43.

Another design for such a gripper can be seen in Figure 13.44. The gripper approaches the object from above. The pins within the object contour are pushed back. Partial withdrawal of the central rod arches the membrane. This in turn causes inclination of the rods thus providing prehension force against the object.



1 gripping pin
2 pin housing
3 object

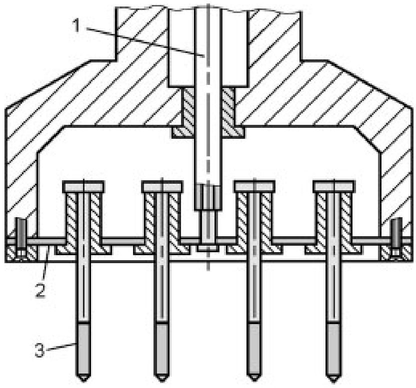
Fig. 13.42: Functional principle of the omnigripper (after *P. B. Scott*)



1 gripper fingers, prehension pins
2 slide
3 angle lever
4 carrier
5 travel rod
6 compliance spring
7 cladding
8 straight line guide

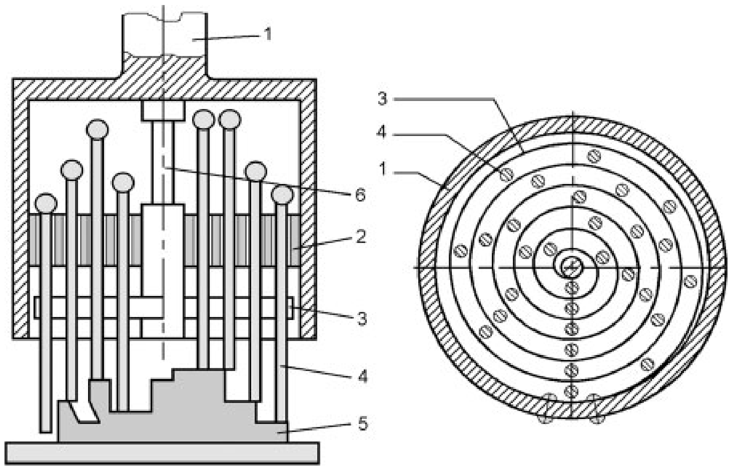
Fig. 13.43: Pin array gripper

A further pin gripper design option is illustrated in Figure 13.45. Its use follows the same scenario as described above. However, the clamping effect is achieved by contracting the fingers within a spiral band. In this case only the pins just beyond the object contour are involved. Once the stress is released and the workpiece ejected, the pins again take their neutral position and are ready for the next gripping operation.



1 central rod
2 spring steel membrane
3 gripping pin

Fig. 13.44: Pin array gripper with membrane



1 housing
2 breaker plate
3 spiral band spring
4 clamped pin finger
5 gripped object
6 rotary drive

Fig. 13.45: Pin array gripper with concentric motion of the moving gripping pins (Russian Patent B 25 J 15/00; 667 397)

13.7.2
Totally Compliant Shape Adaptive Grippers

The handling of delicate materials such as agricultural produce, ornate glassware, unfired ceramics etc., demands special attention [13-14]. Simple impactive implementations will almost certainly result in damage to the prehended object and even the compliance offered by pneumatically driven elastomer fingers as discussed in Chapter 8 are in most cases unlikely to suffice. Consequently, impactive techniques must be augmented by controllable compliance. If the degree of compliance can be controlled by external influences then a gripper can be designed which exhibits quite different prehension and retention characteristics. Such grippers are known as *shape adaptive*.

The evacuation of air from a dry powder or granule filled bag constituted one of the first attempts at shape adaptation for prehension purposes. With this technique the device is made to surround the object to be lifted prior to air evacuation. Once vacuum is applied the device contracts around the object to facilitate a tight grip [13-15]. Similar mechanisms using iron powder and controlled by a magnetic fields have also been attempted, but far better in this respect is the use of “smart” fluids.

Electrorheological [13-16] and magnetorheological [13-17] “smart” fluids undergo a liquid to solid phase change on the application of an electric or magnetic field respectively. Simple gripper fingers [13-18] and complete astrictive gripping surfaces [5-24] employing electrorheological fluids have been demonstrated, though the high field strengths required (up to 3000 volts per mm) make very deep compliant surfaces difficult to implement in practice. On the other hand, magnetorheological fluids have been used very effectively in compliant surfaces used for the polishing of high precision optical components. The use of polymer tendons, where the introduction of different fluids causes expansion or contraction, can also yield a considerable dynamic range of compliance. Caldwell experimented extensively with very thin polyvinyl alcohol sheets which experience swelling when immersed in water. This also has the effect of making the polymer soft and compliant. Acetone is introduced to expel the water and cause contraction of the polymer sheet returning it to a rigid state [13-19]. Unfortunately, most of these techniques remain the domain of research activity with very little (as yet) on the commercial market.

Like most metals, rubbers and polymers such as chloroprene, neoprene, soft PVC etc., exhibit an inverse relationship between elastic modulus and temperature. The glass transition temperature in linear amorphous polymers and co-polymers is defined as micro-Brownian chain-segmented motion involving molecular lengths of 20 to 50 atoms. T_g is the temperature at which the molecular chains have sufficient energy to overcome attractive forces and movement can take place. Above the glass transition temperature T_g these materials are soft and compliant. Below T_g their hardness increases rapidly until they become rigid and eventually brittle. Analogous to shape memory alloys (though the scientific principles are quite different), polymers which experience very large and abrupt changes in mechanical modulus from one side of T_g to the other are known appropriately as shape memory polymers [13-20].

Polymers may be easily formed into foams which have the advantage of providing a three dimensional shape memory material rather than the single axis form commonly available with shape memory alloys. Shape memory foams are available with different compression characteristics and glass transition temperatures covering dynamic ranges of elongation and compression stresses of over 300% [13-14]. In Figure 13.46 the glass

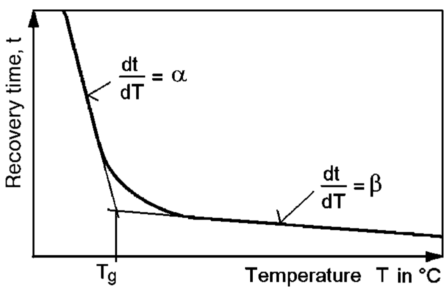


Fig. 13.46: Shape memory foam recovery time against temperature

transition point can be seen between the two quite different recovery characteristics of a typical polyurethane shape memory polymer foam.

In addition to the elastic modulus differential, shape memory foams also have a time response which is temperature dependant. By measuring the free recovery time after depression the characteristic curve of Figure 13.46 is obtained for a sample of shape memory foam with a T_g of 30 °C. From Figure 13.46, the resulting 63 % recovery times can be seen to be governed by two curves, the asymptotes of which converge at T_g. The slopes of the two asymptotes give the expression in (13.1).

$$t = k\,(e^{-\alpha T} + e^{-\beta T}) \tag{13.1}$$

e 2.718
k Material dependant constant

Typical ratios of α to β vary from one to two orders of magnitude depending on the polymer used [13-21]. For any shape memory polymer, the elastic modulus E at a given temperature T can be calculated from (13.2), where E_g is the modulus at the glass transition temperature and α_E is a material constant [13-22].

$$E = E_g \cdot e^{\alpha_E((Tg/T)-1)} \tag{13.2}$$

Like shape memory alloys, shape memory polymers require a finite time for heating and cooling. Furthermore, being polymers they have much lower thermal conductivities than metals. Moreover, in addition to the advantages of being able to be formed into three dimensional shapes, shape memory foams are highly permeable to air thus greatly reducing the time necessary for heating and cooling under forced air conditions [13-22]. This is particularly effective when shape memory foams are to be used for shape adaptive surfaces in robotic prehension as shown in Figure 13.47.

Of perhaps more industrial relevance than the handling of such objects as the soft fruit depicted in Figure 13.47 is the prehension of unfired ceramics and delicate glass components.

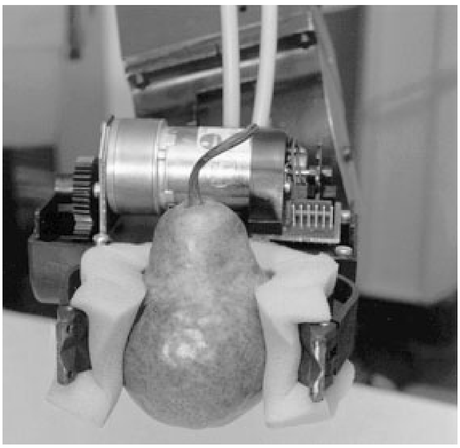


Fig. 13.47: Shape memory polymer foam used in shape adaptive gripping
(Photo: courtesy Brynmoor-Jones Library, University of Hull)

13.8
Collision Protection and Safety

Collisions occur primarily during program development in trial operations and test runs. Protective functions serve to preserve the gripper and object from damage in the case of a collision. Technical means to avoid collisions include: the insertion of predetermined break points in a program, release mechanics for overload protection, collision sensors, shutdown protection and vibration absorbers.

13.8.1
Safety Requirements

Safety aspects can be divided into two groups of interest: collision detection and failure mitigation. The simplest method dating from the early years of robotics, includes a degree of mechanical compliance between gripper and robot flanges, as shown in Figure 13.48. As soon as a predefined force threshold F is exceeded, the gripper is displaced away from the obstacle. An integrated sensor can be used to inform the robot controller of the unexpected movement. Sudden impacts can also be detected by sensors monitoring the arm forces (axial joint sensors) and the robot halted. Unfortunately, the reaction time of the robot controller is rarely short enough to totally prevent damage in cases of high speed operation (see Chapter 11).

The second aspect relates to the preservation of prehension force in cases of power failure. In the following section, some designs will be shown which are relevant to both cases.

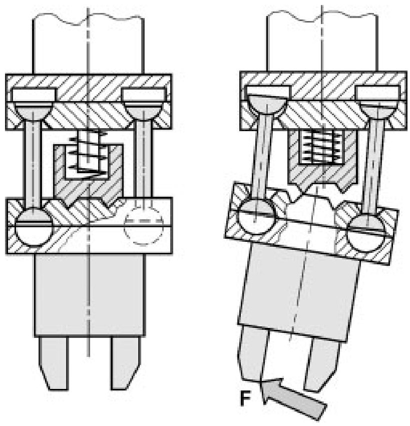


Fig. 13.48: Principle of a simple collision protection
F collision force

13.8.2
Collision Protection Systems

A crash situation with an industrial robot can lead to damage to the endeffector, the robot and the workcell in general. A crash can be caused by unexpected changes in the environment, software errors or the malfunction of some component. Collision protection systems have been developed to prevent, or at least reduce, the consequences.

Figure 13.49 shows one hardware solution. In cases of collision the endeffector is compliant enough to "give" a little whilst simultaneously the robot arm may be halted. Unfortunately, stoppage cannot be realized instantly due to mechanical inertia of the moving mass, reaction time of the robot control software and the electro-mechanics of the robot itself. Pneumatically driven grippers have the advantage of inherent compliance due to the compressed air acting as a spring. The stiffness is dictated by the pneumatic pressure and collision detection can be used to reduce this pressure automatically.

The ability of the system to reset itself subsequent to collision without operator intervention is the domain of "error recovery". This aspect of robotics is largely a research area and will not be further discussed here.

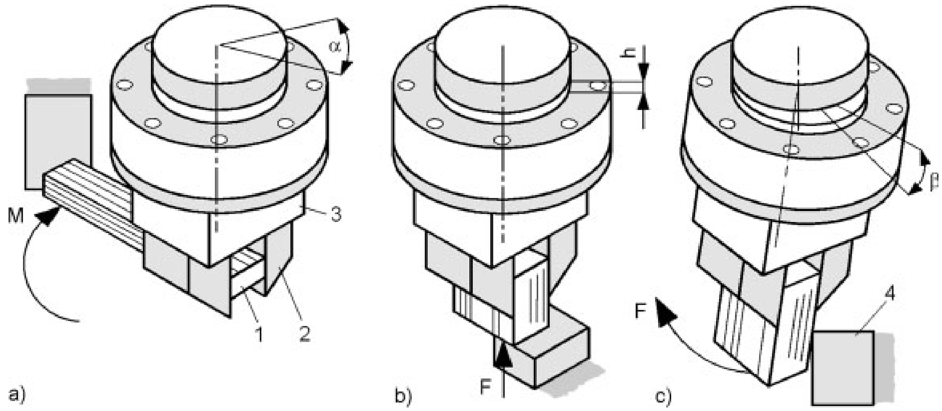


Fig. 13.49: Compliance in a collision protection system
a) releasing on excess torque, b) releasing on crash in x-y direction,
c) releasing on crash in z-direction
1 object, 2 gripper jaw, 3 gripper, 4 obstacle, *F* force, *M* moment

13.8.3
Failure Safety

In many cases of power failure it is preferable that retention force is preserved. Power failure can take the form of a cession in electrical, pneumatic or hydraulic force. In general there are two possibilities:

- **Retention using spring force**
  Upon opening of the gripper a return spring is brought into tension e.g. by a double acting cylinder. Closure is realized using pneumatic and spring forces. In cases of air pressure failure the spring ensures an emergency retention force. Needless to say, the robot should be halted as soon as possible until the power is reinstated.

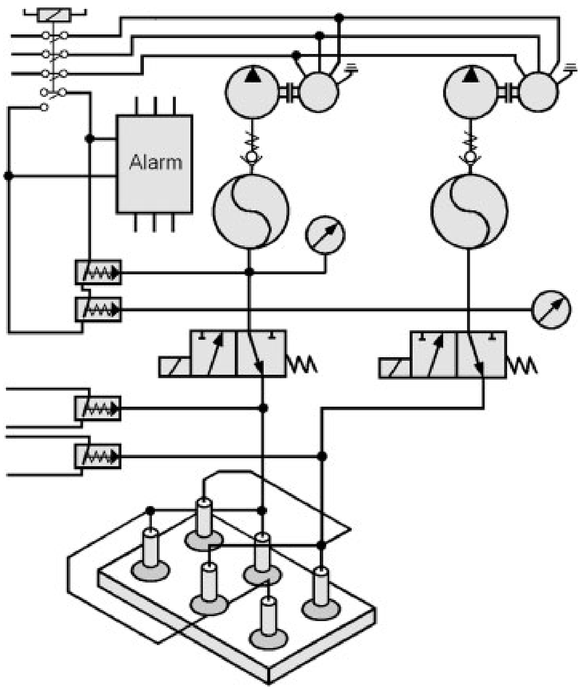


Fig. 13.50: Schematic diagram of a dual circuit vacuum supply

- **Stoppage of the fluid closed loop**
  Overpressure in a pneumatic cylinder which generates the retention force is maintained by non-return valves.

In the case of vacuum suction it is possible to use a dual circuit vacuum generator. As can be seen from Figure 13.50 there are two vacuum pumps. The suction heads are cross-connected in such a way that pressure is maintained if one of the pumps fails. Though somewhat reduced, the residual pressure allows the robot to proceed, albeit with reduced velocity. The total vacuum suction area must be dimensioned in such a way that sufficient retention force remains after malfunction of one suction circuit.

Retention force is often secured using spring packets. The simplest solutions are those in which the principle gripping force is generated by springs (Fig. 13.51 b).

Gripper kinematics using a single cam mechanism constitute only one possible example. The gripper can be designed in such a way that it can accommodate an additional securing cylinder. This safety cylinder intensifies the retention force in the connection scheme shown in Figure 13.51 c. In cases of power failure only the spring force remains active. However, the maintained retention force is lower than that available during normal operation. For the connection scheme shown in Figure 13.51 d the safety cylinder remains inoperable as long as compressed air is applied. In cases of power failure the spring force is activated to maintain the gripper jaws in position, albeit with reduced force.

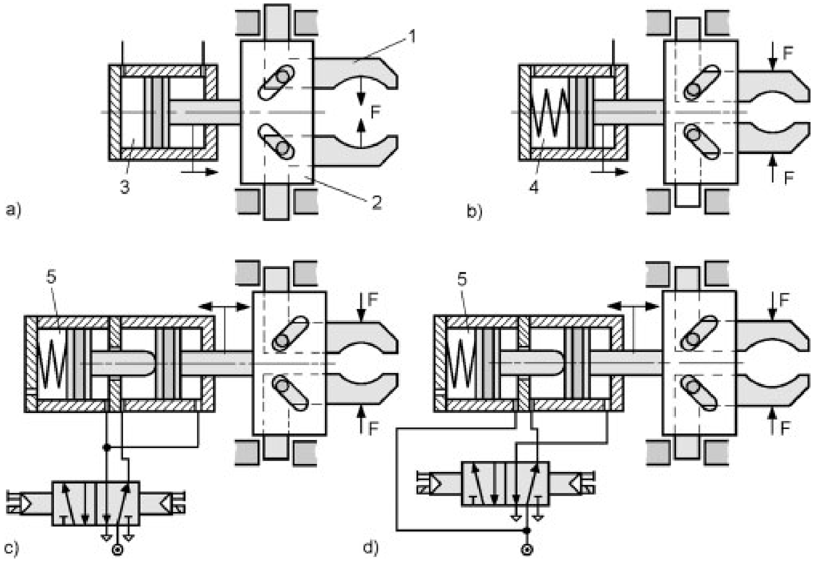


Fig. 13.51: Maintaining retention force in cases of power failure
a) unsecured gripper, b) gripper with retention spring, c) additional safety cylinder,
d) securing cylinder with a modified connection scheme
1 gripper finger, 2 slot guides, 3 double acting cylinder, 4 single acting cylinder, 5 safety cylinder
F retention force

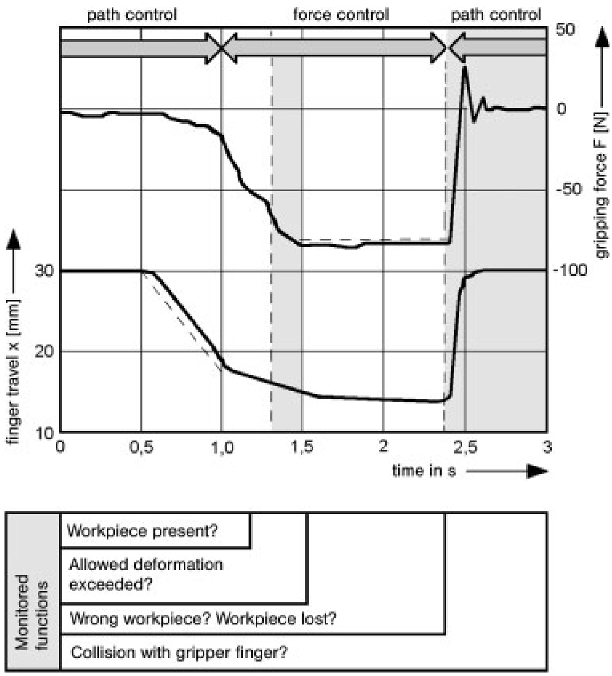


Fig. 13.52: Functions monitored through combined path and force control [13-23]

Using both path and force control, from the characteristic dependence of the finger travel χ on gripping force F, it is possible to determine whether prehension has been correctly performed. The graph in Figure 13.52 explains further analysis of the different gripping phases.

The monitoring of force and path parameters allows recognition of the following situations:

- Presence of workpiece.
- Exceeding the allowed workpiece deformation.
- Acquisition of wrong workpiece or loss of workpiece.
- Collision of the gripper finger with an obstacle.

If the workpiece is not present then full pneumatic pressure will not be reached during closure before the end of the finger stroke is reached. The workpiece deformation in the pressure build-up phase is monitored and limited to a predetermined value. Upon reaching the given prehension limit force the finger travel is compared with that pertaining to the workpiece dimensions. During robot motion, unexpected changes in finger stroke are indicative of loss of the workpiece. Collision of the fingers with obstacles may also be detected by monitoring of finger forces. However, not all possible collisions are observable with such a simple model.

14
Selected Case Studies

This final chapter encompasses many areas of robotic prehension with the help of a number of interesting case studies. The existing patent literature gives the impression that there is always something relating to grippers to be invented. This is not exactly so but nevertheless a lot of efforts are devoted to:

- Refinement or simplification of known solutions.
- Tailoring of suitable grippers to novel applications.
- Extending the field of flexible applications.
- Utilization of physical effects in a new, often surprising way.

Many grippers represent special solutions which are designed for a specific prehension task, often limited to one type of object. At the same time some of their details are quite sophisticated and can be useful for the development of other grippers.

14.1
Simple Telemanipulation

Telemanipulators are devices or tools driven by energy not originating from human (or other living) sources. They support the user in the manual handling of objects. Hand guided telemanipulators originate from nuclear technology where radioactive materials in "hot" segments must be remotely handled. The first unilateral manipulator with mechanical force transmission and an electrically driven manipulator arm was developed in 1947 at the Argonne National Laboratory (ANL) in Idaho Falls (USA). It was the precursor for the mechanical master-slave telemanipulators and the subsequently developed force manipulators with microswitch control. A telemanipulator is controlled by a unit connected to the load carrying equipment and/or by direct and consecutive load guidance. For prehension of the load, a load handling attachment or gripper is needed.

Manipulators employed in furniture manufacturing, civil engineering, and storage sectors are primarily hand guided. They are often referred to also as balancers or compensators. In the simplest case the grippers are manually controlled. Balancers automatically adjust the appending load against gravity during prehension so that the load is held in a state of levitation.

Robot Grippers. G. J. Monkman, S. Hesse, R. Steinmann, H. Schunk

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One distinguishes between:

- Balancers (manually driven manipulator arm).
- Master-slave manipulators (manually guided).
- Force manipulators (force feedback controlled).

They are typically pertinent to the following applications:

- Relatively slow (low throughput) manipulation of very heavy loads (possibly many hundreds of kilograms).
- Special conditions: e.g. shortage of space in storage areas, explosive atmosphere, objects having bulky or bizarre shape.

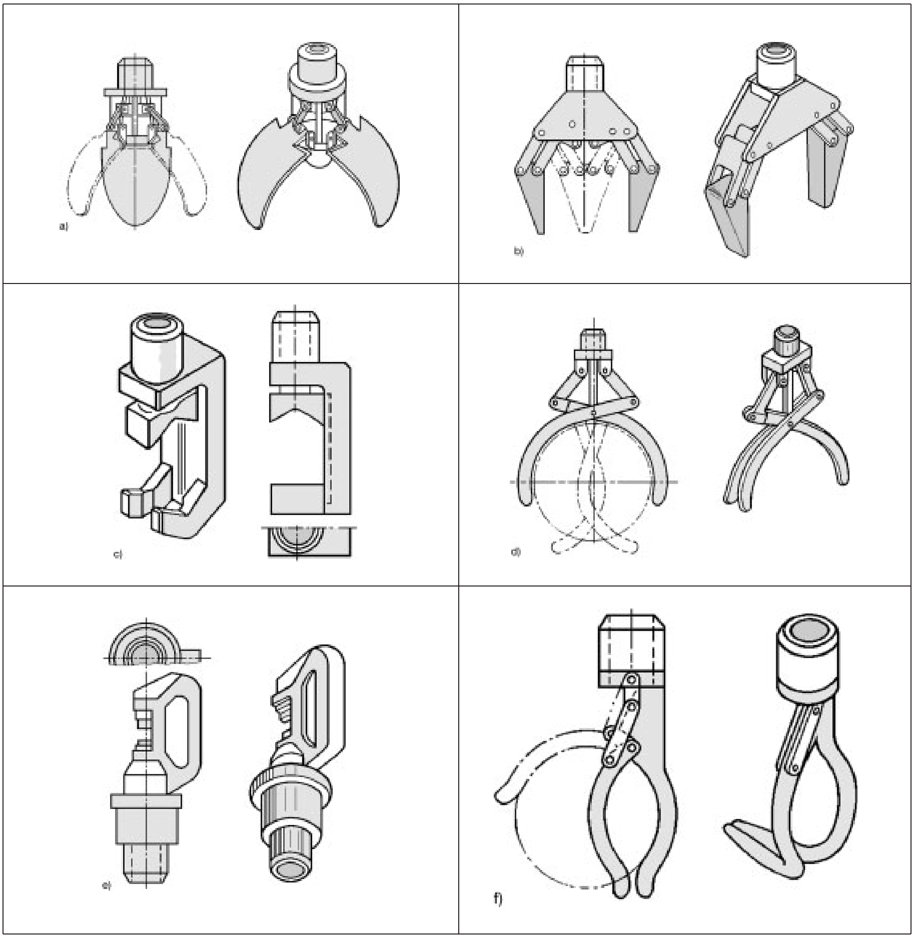


Fig. 14.1: Typical designs for telemanipulator grippers and telemanipulator tools a) shell gripper, b) parallel gripper, c) hook and tube gripper, d) three-finger gripper, e) cable cutter, f) hook grippers with the form of a prosthesis hook which can be employed for impactive prehension.

There are also many special grippers with or without integrated and controllable hand axes. Guided largely by hand and eye, the tasks which can be performed with telemanipulators lack the degree of accuracy and repeatability normally experienced with robots. Grippers for balancers are in general equipped with hand axes for turning, rotation and/or pivoting of objects. Motions of the object can be defined as follows:

Turn: Turning or pivoting of an object about an intrinsic or an extrinsic axis in order to exchange (reverse) the lower and upper sides. This is always a 180° motion.

Rotate: Moving of an object from one definite into another definite orientation about an axis which contains a reference point belonging to the object. The position of this reference point remains unchanged.

Pivot: Rotation of an object into a new position and orientation through motion about an extrinsic axis.

All manipulators require grippers or similar effectors (load handling attachment) in order to be effective. Figure 14.1 shows some design examples.

Figure 14.2 shows some vacuum suction grippers for the handling of packages, concrete and wooden parts. More detailed presentation can be found in [5-18]. Many applications are found in production lines of the automotive industry. The grippers used are usually tailored to the fit the objects, e.g. car wheels, cockpits, exhaust systems, car seats, cylinder heads and auto body parts like doors and hatchbacks.

Figure 14.3 shows the half section of a balancer gripper which is equipped for the handling of cylinder heads. The gripper makes contact with the cast object with centring sockets whilst simultaneously opening the claws. When lifting the object they hook it beneath a nose. The gripper can also grasp the object from beneath [14-1].

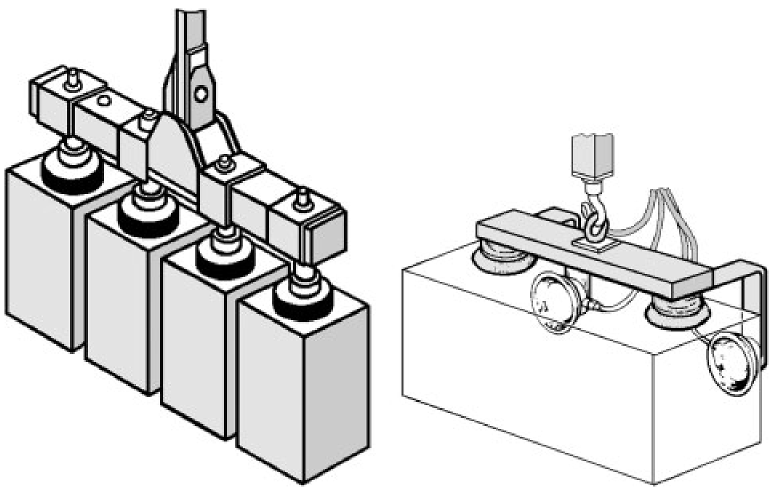
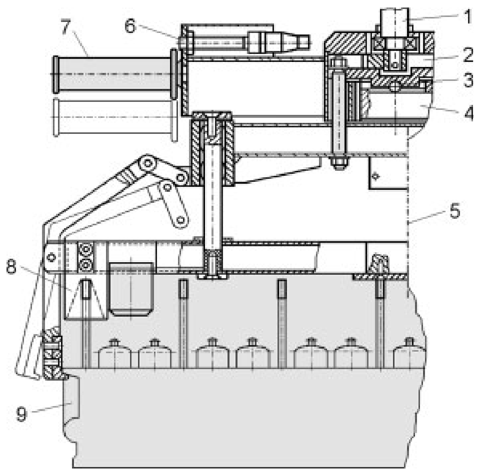


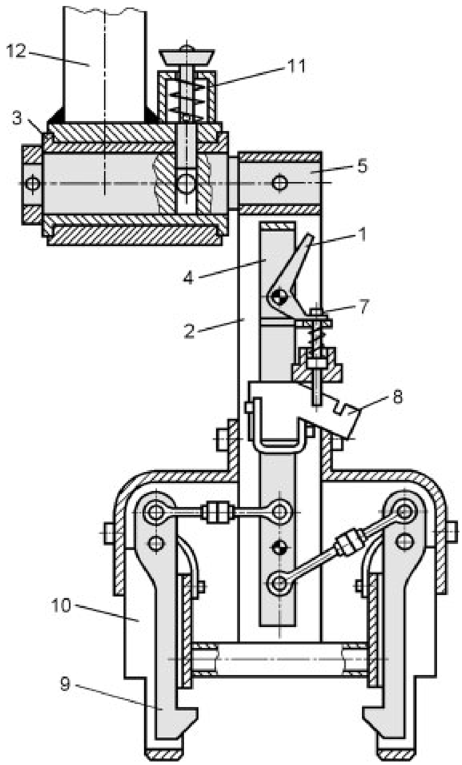
Fig. 14.2: Vacuum suction gripper for hand guided manipulators



1 connection for a balancer
2 manually rotatable by 340°
3 pressure sphere
4 force dynamometer
5 barycentric axis of the cylinder head
6 infrared sensor or microswitch
7 service handle
8 hardened centring cone
9 workpiece, cylinder head

Fig. 14.3: Gripper for the handling of cylinder heads (*Schmidt-Handling*)

Figure 14.4 shows a gripper for the lifting of cases of cuboid form. The gripper fingers can be locked to avoid accidental opening. Moreover, by means of a wrist axis, the entire gripper can be pivoted into the horizontal position.



1 release button
2 connection bridge
3 tube
4 service handle
5 axis
6 leaf spring
7 stop bolt
8 fix stop
9 gripper jaw
10 housing
11 angle adjuster
12 connection to a lifting tool, e.g. a fixed arm balancer

Fig. 14.4: Hook gripper for purely manual manipulation

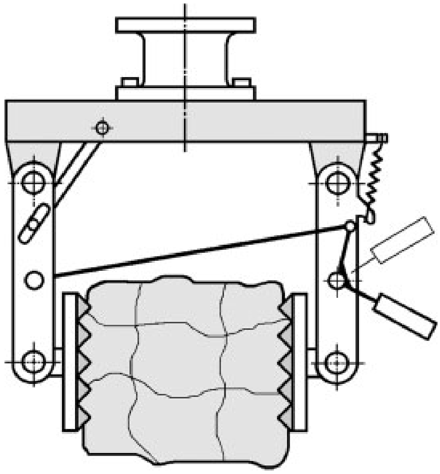


Fig. 14.5: Manually operated gripper for recycling

The gripper shown in Figure 14.5, is intended for objects of varying (and variable) shape: recycled cardboard, paper, textiles etc.

Shell shaped grippers are used for the prehension of bulk materials, garbage, stones, earth etc. Applications include the offshore and undersea sectors, construction, demolition and landfill.

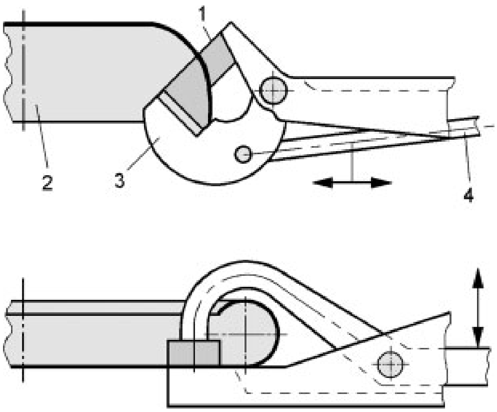
14.2 Grippers for Sheet and Plate Components

The automated handling of sheet metal parts has always been a potential target for automation. Sharp edges and burrs can easily lead to hand injuries, larger parts cannot be handled by a single worker and rationalization (whether manual or automated) reduces overall costs. Compared with other handling tasks the prehension of sheet steel components exhibits the following specific features:

- Highly finished sheet metal components can often be impactively prehended only at the edges.
- When lifted from a limited number of local prehension points, large area metal sheets may distort resulting in positional errors.
- When lifted astrictively, large area metal sheets may be displaced resulting in positional errors.
- Steel sheets are often lubricated with oil or grease to prevent corrosion during storage and consequently exhibit rather low frictional coefficients.
- Thin metal sheets tend to cling together and additional separation may be required when lifting them.

14.2.1
Impactive Grippers for Sheet Metal Handling

For the handling of heavier sheet metal parts, grippers whose prehension principle resembles that of a pipe wrench are often used. One advantage is that it is possible to achieve large jaw openings for relatively small drive strokes. The gripper jaws can be plastic-coated in order to protect the object surfaces, or knurled in cases where surface damage is of little consequence. Figure 14.6 shows two examples of such designs.

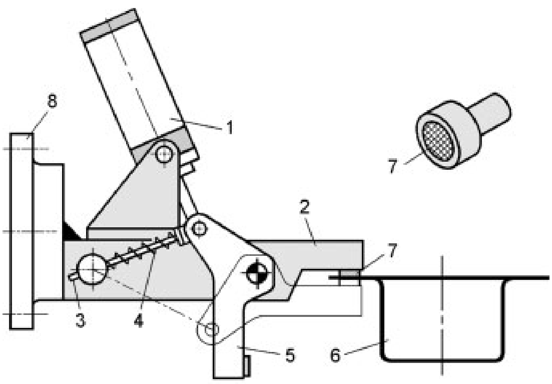


1 plastic or laminate shaped jaw
2 object
3 gripper
4 actuation rod

Fig. 14.6: Impactive gripper for sheet steel clamping

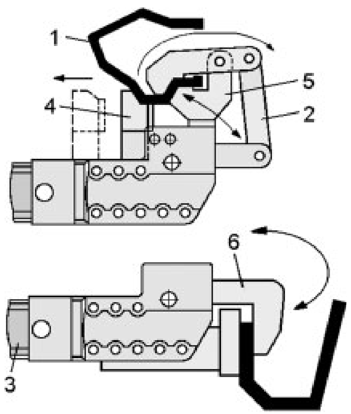
The gripper shown in Figure 14.7 exhibits a large aperture angle. In order to prehend objects at their edges it is sufficient to have only one movable jaw. Closure of the gripper fingers is achieved by converting the linear stroke of a pneumatic cylinder to rotation. Retention force is provided by spring tension, the pneumatic cylinder merely moving the gripper finger over the dead centre of the mechanism. In the opened state the movable gripper jaw is maintained at the end position by the tension spring.

Figure 14.8 shows a very robust clamping module which can be driven pneumatically or hydraulically. In the above example all gripper jaws move simultaneously towards the



1 pneumatic cylinder
2 fixed gripper jaw
3 spring guiding rod
4 tension spring
5 gripper jaw
6 workpiece
7 hardened metal shoe
8 flange

Fig. 14.7: Clamping gripper for sheet steel parts



1 workpiece
2 lever mechanics
3 actuator
4 support jaw
5 gripper jaw
6 pivoting arm

Fig. 14.8: Gripping of sheet steel profiles

workpiece. It is possible to guide the gripper jaw in such a way that it can achieve prehension at points which are curved. Other free space conditions will require different designs with their own particular kinematics. Such grippers are mainly used for heavy workpieces where large moments are involved.

Toggle lever clamps make interesting gripper drives and are commercially available as is shown in the design of Figure 14.9. The depth of movement is adjustable and the arm is actuated over a "half" toggle lever while the rod head is supported by the housing.

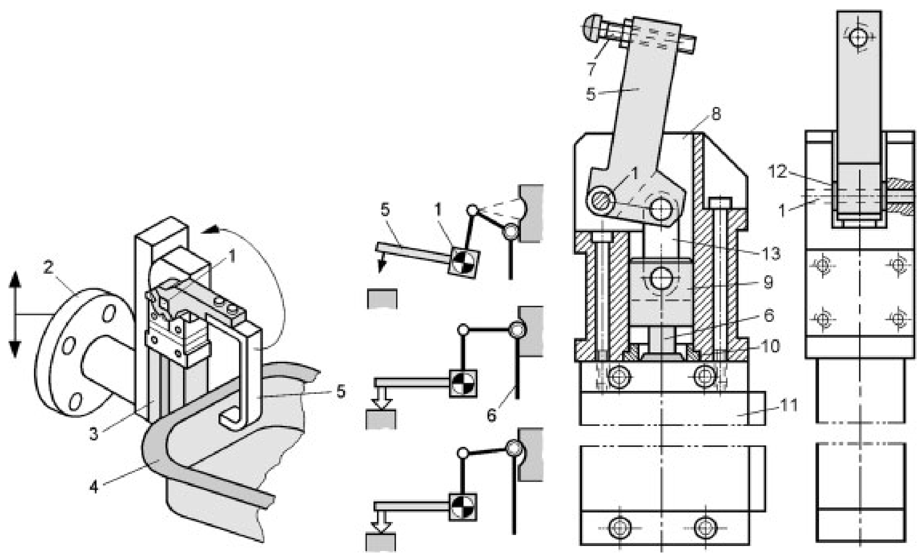
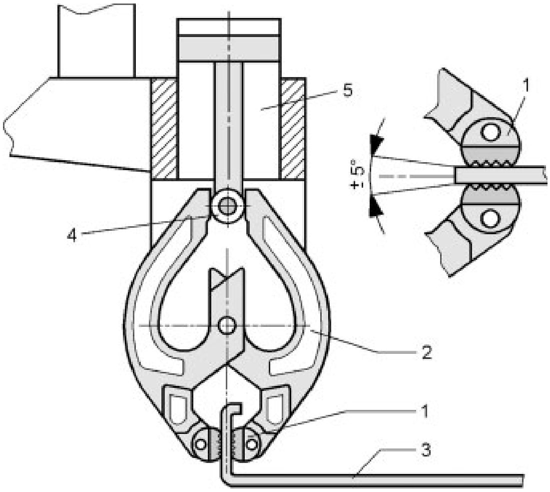


Fig. 14.9: Gripping of large sheet steel parts with a toggle lever clamp
1 clamp shaft, 2 flange, 3 toggle lever clamp, 4 workpiece, 5 spanning arm, 6 cylinder rod, 7 adjustment screw, 8 aluminium housing, 9 guided rod head, 10 bush, 11 pneumatic cylinder, 12 washer, 13 connecting link

The following table contains some data on commercially available clamps, see Figure 14.9 (*Festo*). The given specifications assume an operating pneumatic pressure of 6 bar.

Piston diameter in mm	25	40	50	63
Minimum clamping torque in Nm	35	120	250	450
Minimum holding torque in Nm	90	320	800	1500

In the process of clamping, the mechanics passes through the dead centre in which the prehension force reaches its theoretical maximum. The prehension torque with which the workpiece is maintained adjusts itself in the post dead centre position (at + 4° of the connection link). Hence this design of gripper is self-locking as shown in Figure 14.10.



1 gripper jaw
2 gripping arm
3 object
4 roller
5 pneumatic cylinder

Fig. 14.10: Pneumatically driven self-locking gripper (*BTM*, France)

The gripper presented in Figure 14.11 exhibits similar characteristics. The basic gripper, without jaws, is shown in Figure 14.11 a. This gripper has incremental aperture angles of 0°, 22°, 45° and 75° for each of the two gripping fingers. The modular construction allows for a great variety of modifications.

The variety of possible jaw designs is immense. A few examples are shown in Figure 14.11 b. If necessary it is possible to secure the lower finger (0° angle) and pivot only the upper finger by up to 75°.

Figure 14.12 shows an impactive gripper module. The securable universal ball joint mounting allows adjustment to any arbitrary angle. This can be indispensable for sheet metal parts with freeform surfaces. The exchangeable clamping spikes and screws are usually made from hardened metal [14-2].

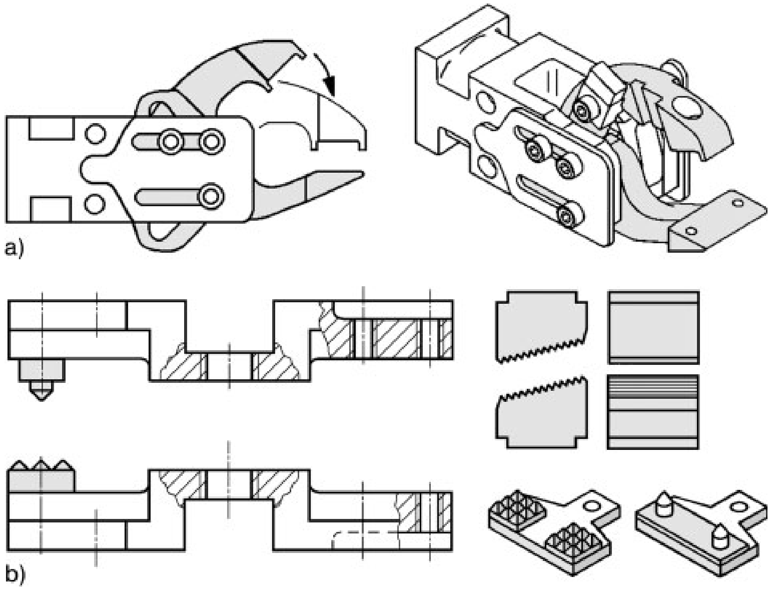
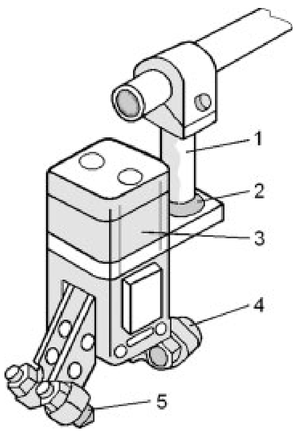


Fig. 14.11: Sheet steel impactive gripper with large aperture angle (*phd,* USA)
a) gripper without jaws, b) examples for gripper jaws



1 mounting arm
2 securable universal ball joint
3 pneumatic cylinder for the jaw actuation
4 pressure screw
5 hardened spike

Fig. 14.12: Impactive gripper module

14.2.2
Astrictive Grippers for Sheet Metal Handling

Grippers designed for large metal sheet handling can themselves turn out to be very large. Typical examples are to be seen in the automotive industry. Hence the arms which are equipped with two-dimensionally distributed suction cups are often referred to as "suction spiders". One first such example is illustrated in Figure 14.13.

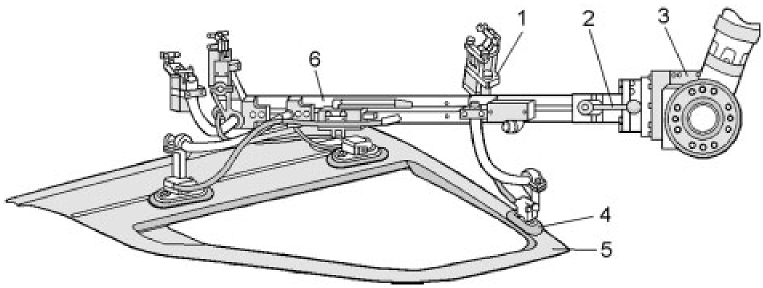
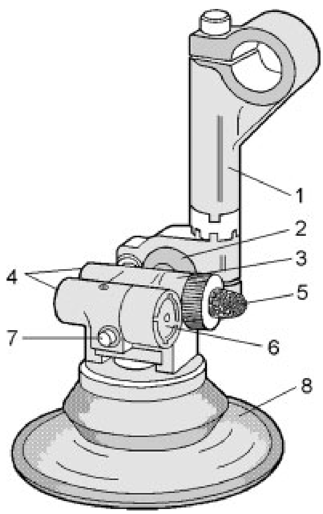


Fig. 14.13: Gripper combination for large sheet steel parts
1 impactive gripper, 2 changing device, 3 robot wrist, 4 vacuum suction cups, 5 sheet steel object, 6 cantilever arm

The arm of the gripper can be rotated by 180° to allow appropriate selection of the impactive or astrictive gripping heads. The impactive jaws are used when the blank sheet is to be inserted into a press. The finished part is somewhat lighter and all surfaces are considered to be sensitive to potential damage. Consequently, after leaving the press only vacuum suction heads are used. All gripper components are designed as modules so that it is possible to match the gripper configuration to the workpiece shape and size.

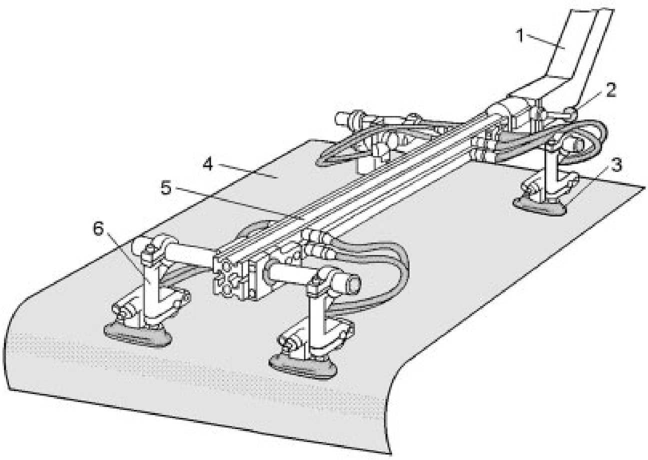
The vacuum suction module depicted in Figure 14.14 is also characterized by its flexibility of positional adjustment. Suction caps rapidly wear out and must be easily replaceable. This is realized by the use of a quick release button.

Figure 14.15 once again shows the configuration of a "suction spider" assembled from modular parts. The cantilever arm is connected to the robot arm over a hand operated exchange system. Cantilevered grippers substantially enlarge the operating range of the robot. The hollow aluminium profiles of the cantilever arm house the necessary compressed air lines.



1 mounting arm
2 spherical head
3 silencer
4 compressed air connection
5 blow-off equipment
6 Venturi ejector
7 quick release for suction cap exchange
8 disk suction cap

Fig. 14.14: Vacuum suction module



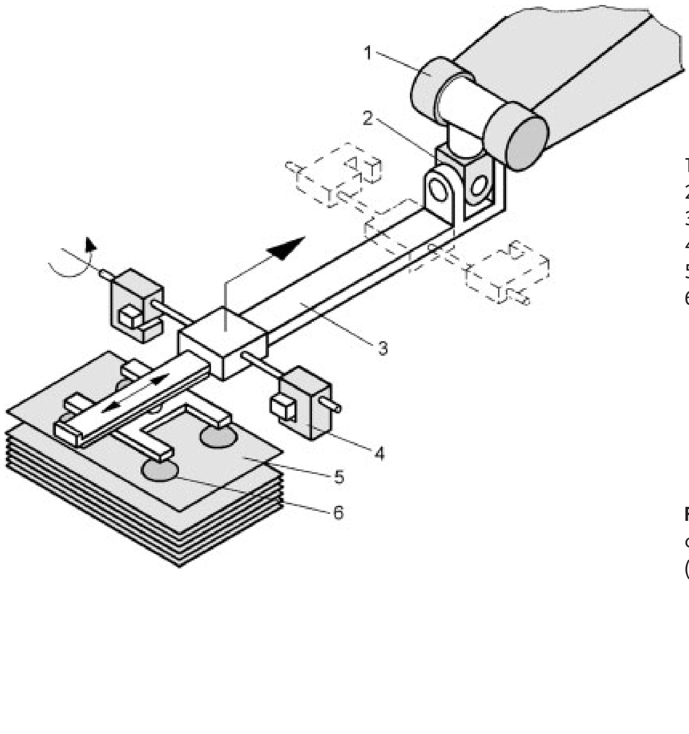
1 robot arm
2 coupling
3 oval suction cup
4 metal sheet
5 cantilever arm
6 suction module

Fig. 14.15: Design of a large area suction gripper

When metal sheets are to be lifted from a stack, due to surface tension, contaminants etc. it is possible that additional sheets will adhere to the first. This can present problems in an automated system where manual intervention is undesirable. Details of separation techniques, many of which are also applicable to metal sheets, can be seen in Chapter 10.

There are a number of strategies which may be implemented:

- Arching of the sheet during prehension to expel surplus sheets (see Fig. 10.3).
- Mechanical or optical thickness measurement to detect surplus sheets.



1 robot
2 wrist
3 linear translation unit
4 adjustable sheet feeler
5 gripped sheet
6 vacuum suction cup

Fig. 14.16: Double sheet control with a feeler (*Englert*)

And for ferrous materials:

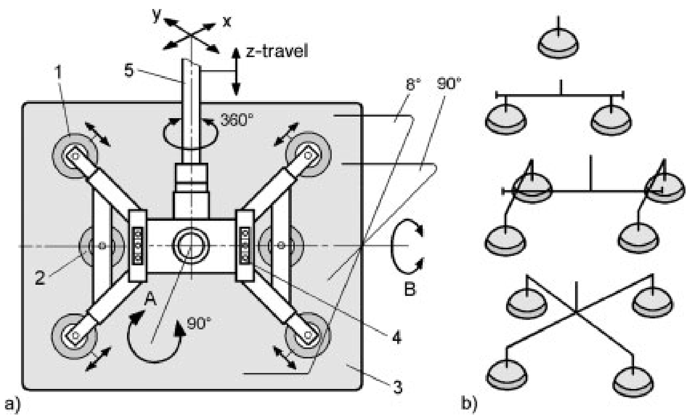
- Inductive sensors may be used to measure the electromagnetic properties to detect surplus sheets (see Chapter 11).
- Using magnetic force to separate surplus sheets after acquisition using vacuum heads.

One solution is shown in Figure 14.16. The thickness template is adjustable and is pivoted away after the check in order to avoid interference after acquisition.

14.2.3 Astrictive Grippers for Glass Sheet Handling

A prerequisite of using vacuum suction techniques is low porosity of the workpiece material. A gripper suitable for the handling of large metal or glass plates and composite or plastic boards is presented in Figure 14.17. Each of the 6 suction cups has its own ejector and the complete system is capable of generating prehension forces as large as 1500 N.

Separation of like parts from one another was discussed in Chapter 10. In some cases further operations, integrated with the prehension process, may be required.



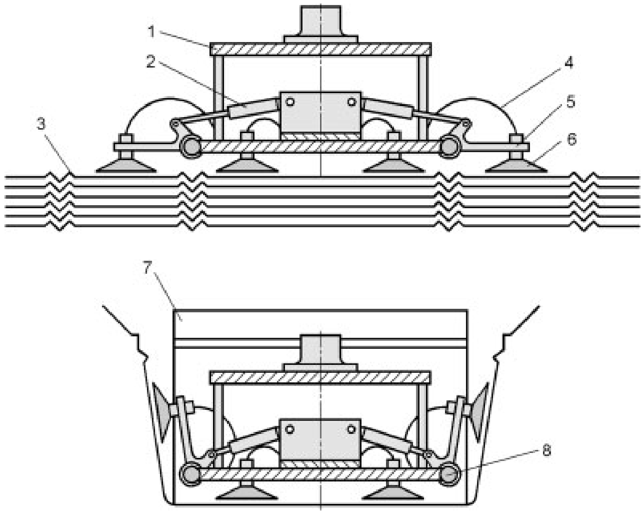
1 adjustable suction cup
2 fixed suction cup
3 prehended object
4 ejector
5 robot arm

Fig. 14.17: Handling of plates with vacuum suction
a) vacuum cross-beam, b) suction cup configurations

14.2.4 Astrictive Grippers for Composite Material Handling

The gripper shown in Figure 14.18 is intended for the acquisition and separation of large carton blanks which are provided lying flat in a stack.

Following successful prehension, the external suction caps are pivoted inwards so that the carton sides are set upright. For this purpose the pivoted suction heads are arranged at all four sides of the base plate. The sequence proceeds as follows:



1 gripper frame
2 pneumatic cylinder
3 corrugated carton blank
4 vacuum line
5 pivoted gripper arm
6 suction cap
7 carton blank, set upright
8 base plate with swivel joint

Fig. 14.18: Prehension and folding of carton blanks

- Separation of one carton blank from the stack,
- Setting all four sides upright at 90° and
- Deposition of the folded carton into the retainer of the packaging line.
- Finally, the same gripper is used to prehend the products and insert them into the carton. In this case the pivoted suction heads remain in their upright position.

14.3
Prehension of Cuboid Objects

Packages and cartons are characterized by their predominantly cuboid shapes. What differs is their size, mass and surface properties (foil, wood, plastic, cardboard). When packing, stacking or relocating the pieces it must be decided which surfaces (sides) are most suitable for prehension. If astrictive prehension can be achieved solely from above then the task is relatively simple and all operations can be performed in an arbitrary sequence as shown in Figure 14.19 a.

Heavy objects may require astrictive prehension on up to three surfaces. However, impactive grippers may also be a possible alternative as long as access to the surfaces is possible. The use of gripper jaws made from thin and preferably flat sheet (hard-chromium plated) steel are helpful in such circumstances. Fork and clamping grippers are not usually suitable for de-palletizing because of access problems.

Containers, boxes and cases of widely varying sizes can be a problem where impactive methods alone are to be used. Suitable prehension force is rarely available in cases of extremely large gripper stroke. However, impactive prehension can be augmented with astriction (usually vacuum suction) as illustrated in Figure 14.20. Each gripping procedure begins with positioning of the jaws which is then followed by vacuum suction. Since the movement of the gripper fingers is mechanically coupled, the mass centre of gravity always remains in the middle.

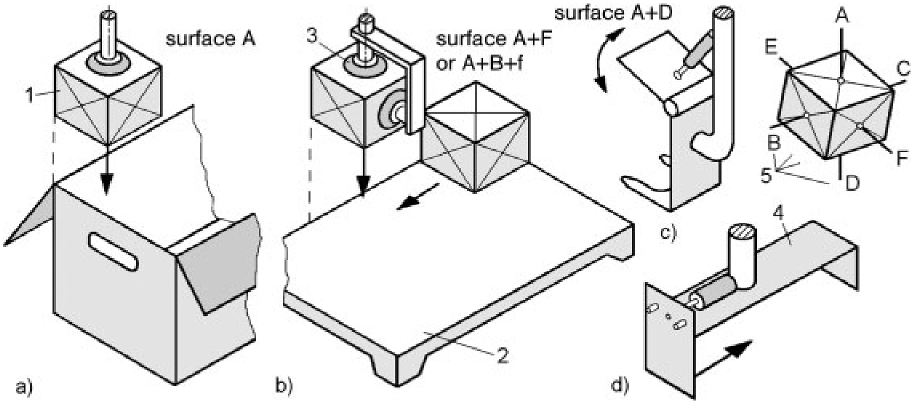
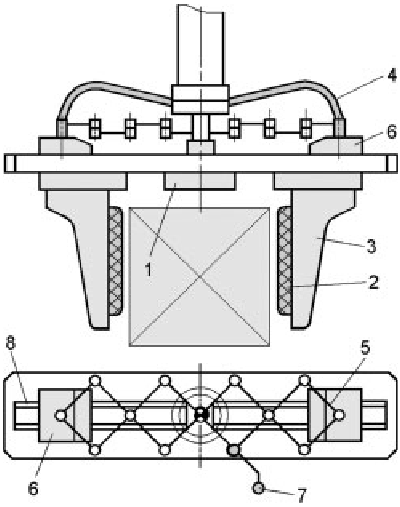


Fig. 14.19: Principles of gripping in packaging and stacking procedures
a) single suction head, b) angled suction pair, c) fork gripper, d) impactive gripper
1 package, 2 pallet, 3 suction cup, 4 impactive gripper, 5 product surface labelling

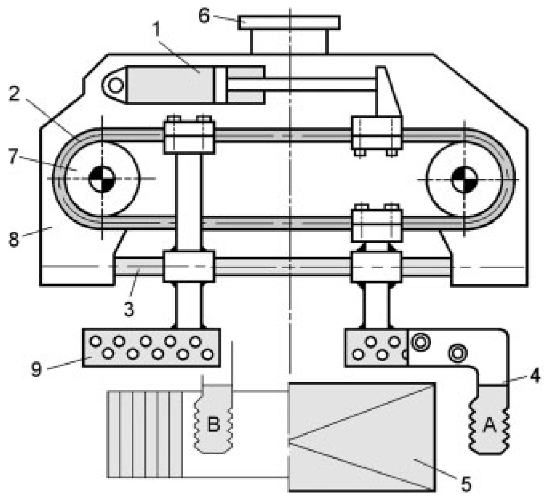


1 mechanical connection
2 suction plate
3 large stroke gripper jaw
4 vacuum tube
5 shear mechanism
6 slide
7 hand lever
8 straight line guide

Fig. 14.20: Combination of impactive and astrictive prehension (*Schmalz*)

Similar to the design in Figure 14.20, the gripper shown in Figure 14.21 is characterized by a very large stroke limited only by the stroke of the double acting pneumatic cylinder. This allows the handling of a large range of package dimensions with both external and internal grip. In addition, the gripper jaws can be displaced along a hole grid (or tooth raster).

Grippers intended for the handling of large volume objects must not necessarily use long stroke actuators. One alternative uses pneumatic muscles. In the example shown in Figure 14.22 a the muscles are deformed over the pull rod with the rubber roller which produces prehension.



1 pneumatic cylinder
2 rope, chain or toothed belt
3 linear guide
4 gripper jaw with adjustable stroke
5 object
6 flange
7 pulley
8 base plate and housing
9 hole grid for attachment of the jaws

Fig. 14.21: Long stroke gripper for packages

The gripper design is simple, of modular construction and is lighter than similar designs employing pneumatic or hydraulic cylinders. There is no direct contact between hard metal parts and the objects surfaces. This has distinct advantages in the handling of objects with sensitive surfaces, e.g. coated, polished, printed etc.

For the gripper shown in Figure 14.22 b, the force of the muscle is transformed into finger motion. Such pneumatic muscles can withstand at least 10 million load exchange

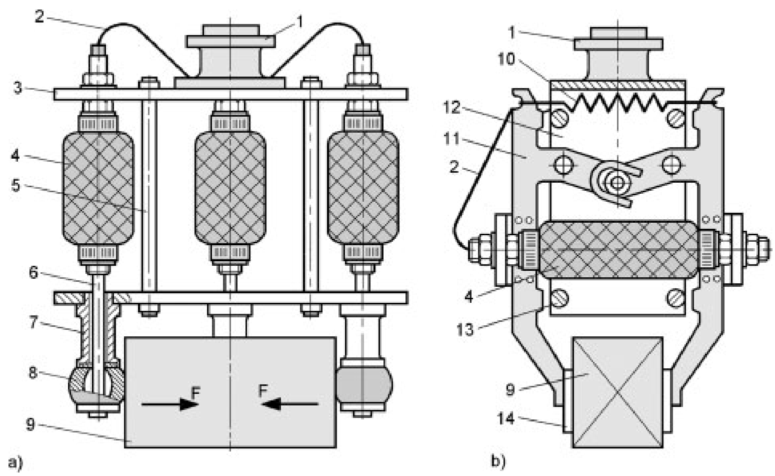
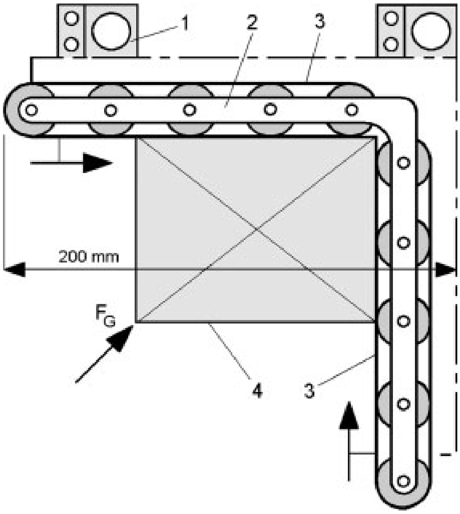


Fig. 14.22: Impactive gripper using pneumatic muscles (*Festo*)
a) four-finger gripper, b) jaw gripper
1 gripper flange, 2 compressed air line, 3 base plate, 4 pneumatic muscle, 5 spacing bolt, 6 pull rod, 7 guide jacket, 8 rubber roller, 9 workpiece, 10 retaining spring, 11 gripper finger, 12 carrier, 13 end stop bolt, 14 gripper jaw



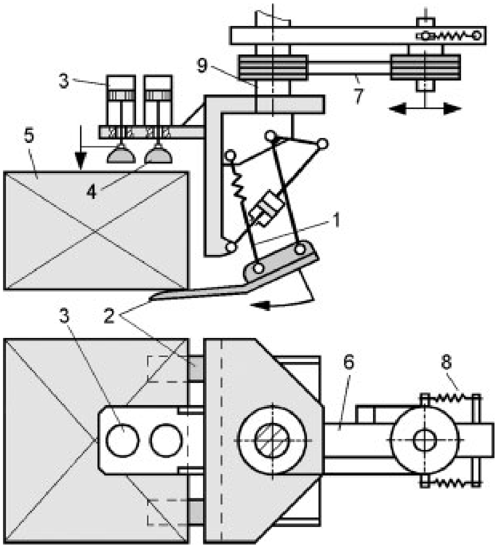
1 drive motor
2 gripper frame
3 high friction belt
4 object

F_G effective gripping force

Fig. 14.23: Traction gripper (Fraunhofer Institute for Material Flow and Material Logistics, Dortmund, Germany)

cycles. Further advantages are lower power consumption than for comparable cylinders and, because they are hermetically sealed, insensitivity to dirt, water and dust ingress.

Figure 14.23 shows a new principle for the prehension of regular cuboid shaped objects similar to the roller gripper in Figure 10.14. The gripper consists of two prehensive surfaces comprising high frictional coefficient belts. When the gripper is applied to the orthogonal surfaces of an object, the reverse sides of the belts produce a frictional force which pulls the object into the rectangular corner. To some extent the traction forces can be controlled by the drive motor torques.



1 balance rod
2 fork
3 pneumatic cylinder
4 pressure pads
5 object
6 handling equipment arm
7 supply lines
8 tensioning device for supply lines
9 swivel axis

Fig. 14.24: Carton gripper

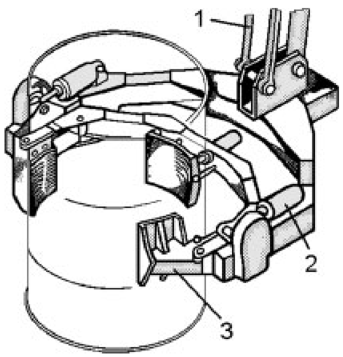
The gripper is suitable for the grasping of packages which are stacked or arranged on a pallet with little intermediate space. As previously shown, this principle can also be applied to sacks, tubes and objects with spherical shape up to 10 kg.

Figure 14.24 illustrates a carton gripper resembling a fork-lift mechanism. The flat fork is inserted under the carton. The pneumatic cylinder drives the fork further until the object is pushed against the stop of the base plate. In addition, the angle of the fork is adjustable over the four joint linkage. The acquired object is then secured by downward movement of the pressure pads connected to small pneumatic cylinders. A double-check valve, integrated into the compressed air circuit, ensures retention in cases of sudden power failure.

14.4 Prehension of Cylindrical Objects

Many different grippers have already been developed for the handling of barrels and gas cylinders. They can be grasped at the shell surface, the cover surface or, if available, at one of the reinforcing seams (see Fig. 3.119).

Figure 14.25 shows an impactive gripper designed specifically for the handling of heavy cylindrical objects. Two jaws, designed with large area in order to keep the surface pressure low, are driven from a single pneumatic or hydraulic cylinder.

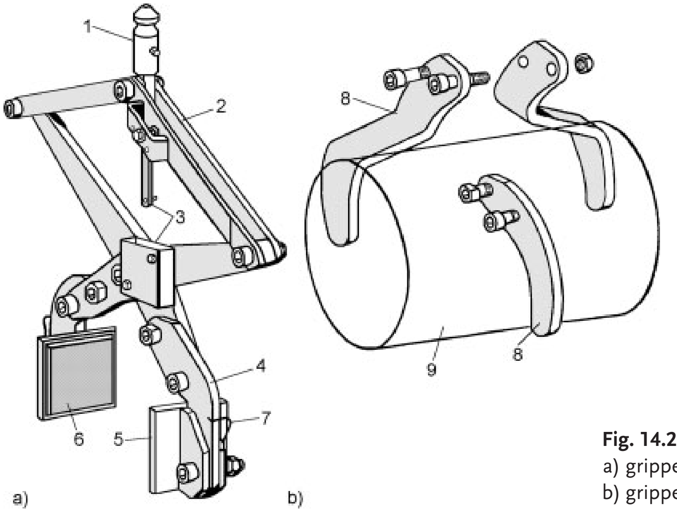


1 manipulator arm
2 pneumatic cylinder
3 impactive jaws

Fig. 14.25: Three-point impactive gripper for the handling of barrels

In the example given in Figure 14.25 the gripper may be attached to a hand guided jointed-arm manipulator. This is also the case for the gripper presented in Figure 14.26 which can only grasp the barrels from a horizontal position. This is realized by the claw fingers with three point contact. The jaws are exchangeable and the flat cushioned jaws shown in Figure 14.26 a are intended for the prehension of cuboid shaped objects.

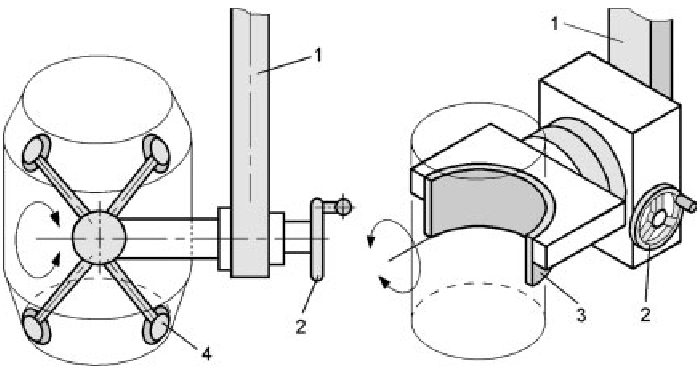
Objects are automatically clamped through the redirection of mass forces during lifting. A hook is engaged on deposit which maintains the jaws in the open state ready for the next acquisition and lifting operation.



1 coupling adaptor end
2 rhomboid mechanics
3 locking mechanism
4 exchangeable fingers
5 gripper jaws
6 rubber overlay
7 safety wire for securing nut
8 jaws for cylindrical objects
9 object

Fig. 14.26: Exchangable gripper jaws
a) gripper jaws for cuboid objects
b) gripper jaws for cylindrical objects

One example for the prehension of barrels with vacuum has already been presented in Figure 5.29. Grippers, comprising several distributed single suction cups or one curved suction plate, can also be used for astrictive prehension at the shell surface. However, the latter is applicable only for a defined barrel radius. The grippers demonstrated in Figure 14.27 are also normally attached to hand guided manipulators.

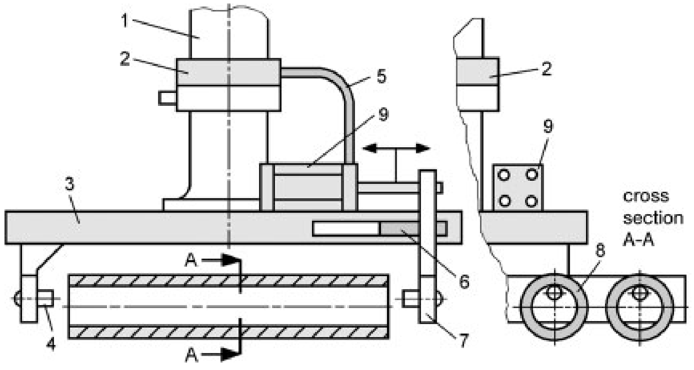


1 manipulator arm
2 hand driving shaft
3 suction plate
4 suction caps

Fig. 14.27: Astrictive barrel grippers

14.4.1
Serial Prehension of Tubes

The gripper presented in Figure 14.28 was designed for the serial removal of tubes from a conveyor line. The gripping hook bar is positioned by gripper closure through a pneumatic cylinder thus prehending the tubes internally. It is important that the objects are presented by the conveyor at intervals corresponding to the separation of the gripping hooks.



1 robot
2 flange
3 base frame
4 gripping hook
5 compressed air line
6 hook guidance
7 gripping hook bar
8 workpiece
9 pneumatic cylinder

Fig. 14.28: Multiple gripper for tube sections

14.4.2 Prehension of Wound Coils

The handling of wire coils presents a number of problems largely dependant on the nature of the finished product and their respective customers. Coils of steel wire intended for garden fences require less attention to damage avoidance than thinly insulated copper wire coils awaited by an electric motor manufacturer.

Given the former scenario, as can be seen from the grippers depicted in Figure 14.29 both external and internal prehension of the coils is easily realised. Both grippers have a stop for actuation of the jaws on contact with the coil and an arrest hook in order to maintain the gripper jaws open during deposit. Retention is achieved through the object mass forces. The mechanics of an impactive gripper design intended for the handling of vertically orientated coils can be seen in Figure 3.118 in Chapter 3.

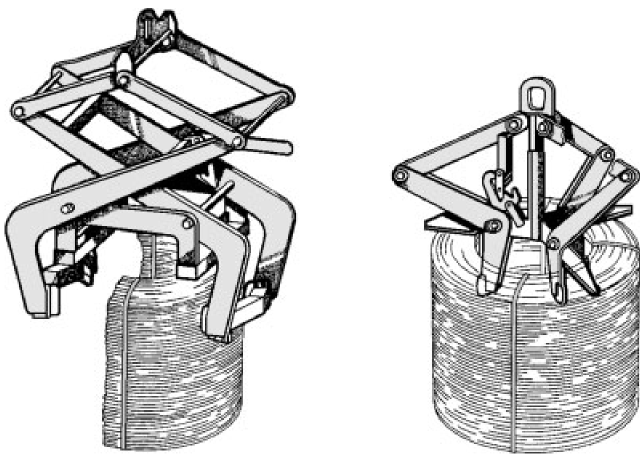
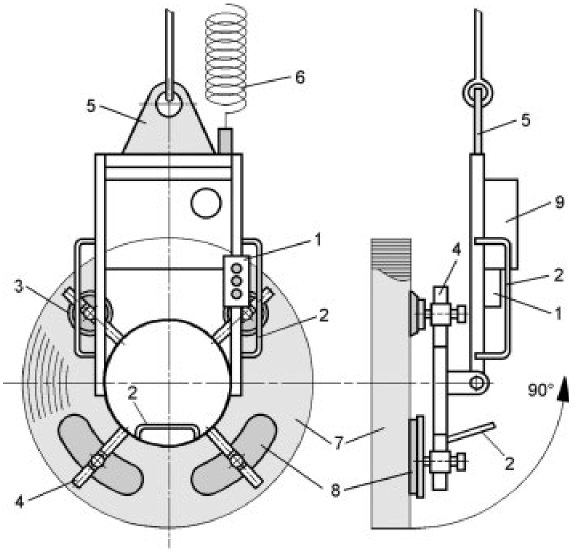


Fig. 14.29: Coil gripper (*Pfeifer*). Left: external gripper, Right: internal gripper

14.4.3
Prehension of Slit Coils

Thin and narrow metal bands with thicknesses as low as 0.1 mm are rolled onto formers at the end of the production process. The lifting with a loop and crane can cause damage to the band as a result of the coil mass (up to 1000 kg). As a rule the coils are supplied in the horizontal position. It order to be loaded on site they must be taken into a decoiler, but first rotated by 90° before being delivered onto the decoiler arms. This procedure should not lead to telescoping (slipping of separate layers from the sleeve) of the coil. The decoiler arm should be fully inserted into the inner diameter of the coil.

Vacuum suction heads have proved to be an almost ideal prehension method for this purpose since they grasp the sleeve by a plane system of suction plates. One example of such equipment is shown in Figure 14.30. The pivoting by 90° in this example is realized manually though pneumatically driven devices also exist. The suction heads can be adjusted to the coil diameter. If the sleeve is not wound with sufficient density the resulting leakage can lead to substantial reduction in retention force.



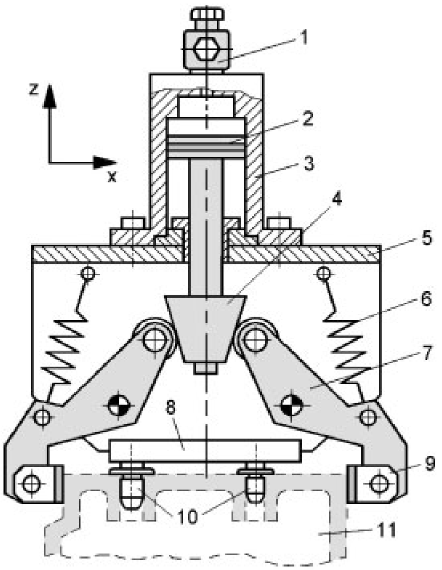
1 service unit
2 lead grip
3 suction caps
4 suction cap arm
5 attachment lug
6 compressed air supply (6 to 7 bar)
7 coil
8 curved suction plate

Fig. 14.30: Load-carrying equipment for narrow slit coils with masses up to 300 kg (*Anverra*)

14.5
Prehension of Objects with Irregular Topology

14.5.1
Handling of Castings

Figure 14.31 shows a pneumatically driven gripper for which the object, in this case an iron casting, is first centred and then clamped. The plate with the centring elements can be designed as an exchangeable component in order to have greater flexibility in handling



1 compressed air connection
2 piston
3 cylinder
4 wedge
5 gripper plate
6 return spring
7 gripper finger
8 feeder plate
9 gripper jaw
10 centring bolt
11 workpiece

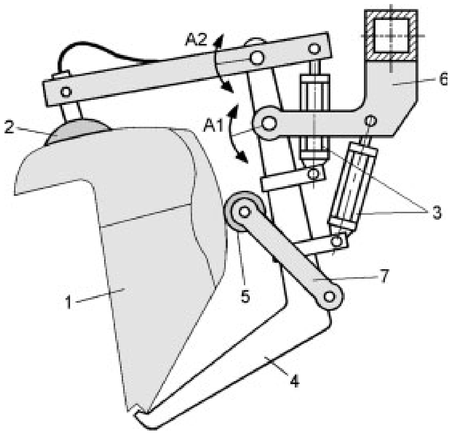
Fig. 14.31: Two finger gripper with a centring aid

different shaped objects. Centring within the gripper is necessary when a mounting procedure follows or when deposition which requires exact positioning with respect to the *Tool Centre Point* (TCP) is required.

Very heavy iron castings usually require gripper actuation by means of hydraulic, rather than pneumatic, cylinders.

14.5.2
Mounting of Dashboards for Automobiles

Dashboards are irregular, pre-shaped and bulky structures which often make difficulties for handling and manipulation equipment. Tolerances can be rather rough and mounting



1 object
2 suction cap
3 pneumatic cylinder
4 support arm
5 support roller
6 manipulator base plate with connection profile
7 adjustable roller arm

A axis

Fig. 14.32: Gripper for manipulation of car dashboards (*Strödter*)

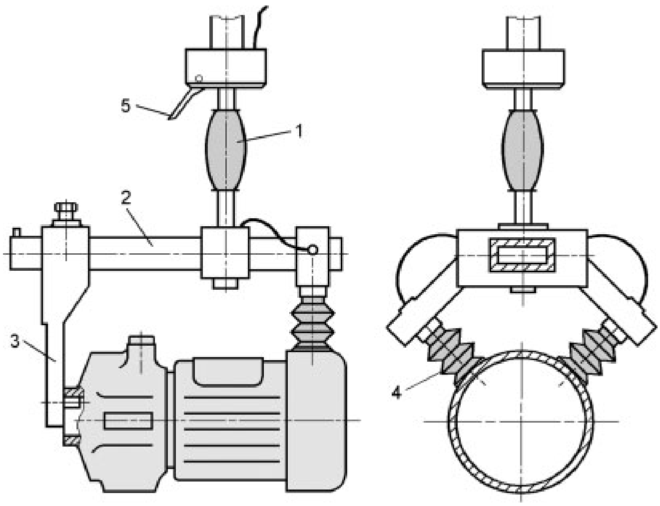
requires several operators who must juggle with a mass of about 40 kg in order to install it without damage. A handling device with a large degree of position compensation offers distinct advantages. The gripper capable of installing dashboards within 2 minutes, while the automobile body is in motion [5-18], is shown in Figure 14.32.

14.5.3
Prehension of Water Pumps

The gripper designed for water pumps shown in Fig. 14.33 utilizes two gripping principles:
- Shape-matched underhooking with a mandrel.
- Astrictive prehension of the motor fan housing through vacuum suction.

The gripping organs are arranged with a possibility for adjustment so that the mass centre of gravity can be aligned with respect to the vertical axis of the handling device. It is also possible to grasp other water pumps of different sizes.

The switching of vacuum is initiated at the service lever and the load is guided manually with the service handle. The service of the gripper is secured in such a way that the load is released from the gripper only if it has already been deposited on a stable support.



1 service handle
2 cross-beam
3 adjustable clamp arm
4 suction bellows
5 vacuum control valve

Fig. 14.33: Lifting of water pumps (*SMI*)

14.5.4
Astrictive Prehension of Irregular Surfaces

Suction bellows are characterized by large mobility and their capability to adapt to parts with uneven or differing surface profiles. Their intrinsic suspension ensures height compensation. The allowed inclination angle α, for the case presented in Figure 14.34, can be between 5° and 40°.

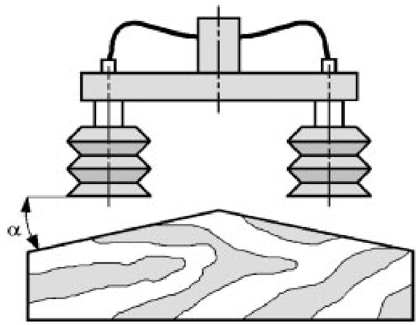
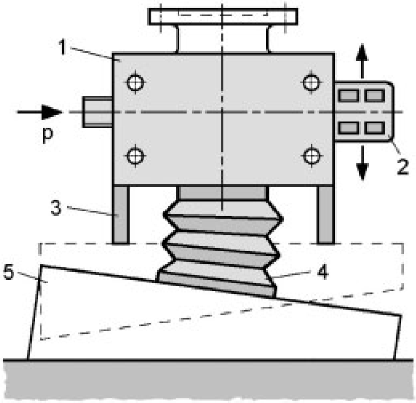


Fig. 14.34: Gripping of a pentagonal workpiece

With the help of stops it is possible to orientate a workpiece with an inclined prehension surfaces to a horizontal position, as illustrated in Figure 14.35. In a similar way it is possible to alter the alignment of a straight workpiece to a given angle.



1 vacuum suction generator
2 sound absorber
3 stop
4 suction bellows
5 workpiece

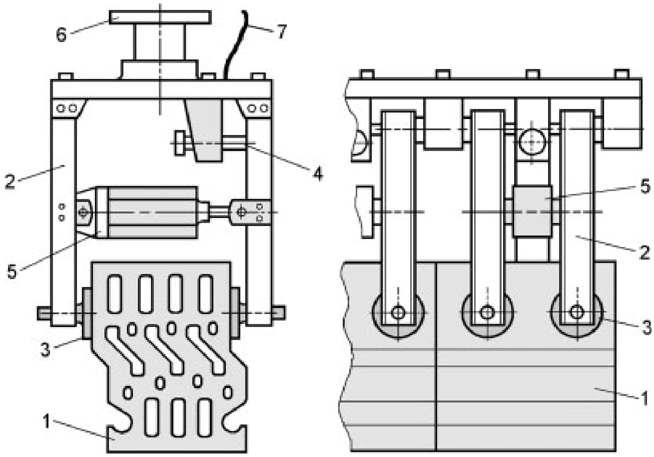
p compressed air

Fig. 14.35: Suction with adjustment supports

14.6 Multiple Object Prehension

In the stone and ceramics industry it is often necessary to manipulate single or several grouped objects. As a rule bricks must be handled in series, for example, as they come from the production line in a close sequence on a plate conveyor. Owing to the low tolerance of the bricks, the handling of several pieces together is possible only if tolerance compensation is available or if several independent grippers are arranged in a row. This is shown in a simplified form in Figure 14.36.

One of the gripper jaws is closed in such a way that the bricks are grasped in a straight line. Now they can be deposited in series on a flat pallet for shipping. This gripper is used primarily in hand guided manipulators (balancers).

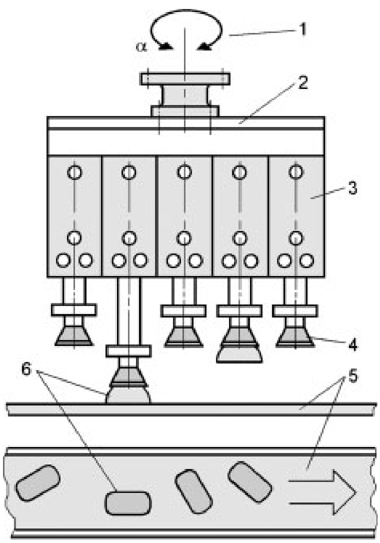


1 bricks
2 gripper jaws
3 gripper fingers
4 mechanical stop
5 pneumatic cylinder
6 flange
7 pneumatic line

Fig. 14.36: Serial gripper for bricks

14.6.1 Packaging of Candies

A high degree of flexibility is required when objects, which require exact positioning, are delivered by a conveyor without any spatial order. Such is the case with wax candles which must be loaded into blister packages. Prehension from a running conveyor requires an image recognition system. The camera is mounted above the conveyor and provides information on the position and orientation of the objects. The gripper shown in Figure 14.37 picks up five objects one by one and rotates them through the required angle before depositing all pieces simultaneously in a row into blister pack forms. The angle of rotation α must be adjusted before the corresponding suction cup descends. The suction cups are



1 NC-rotation axis (axis of the robot hand)
2 top piece – angle plate
3 standard cylinder with skew protection
4 suction cup
5 conveyor
6 “workpiece” (sweets, candies, etc.)

Fig. 14.37: Multiple head suction gripper for deposit operations

attached to standard single-action cylinders with skew prevention (keyed or oval piston – rods) and each can be driven independently of the others.

14.6.2 Bottle Palletization

Figure 14.38 shows a pneumatic gripper for the simultaneous prehension of two dimensional arrays of bottles. The bottles are held in rows by means of an inflatable elastomer pressure cushion, a compliance principle already presented in Figure 13.38 in Chapter 13.

During inflation, the elastomer profile complies with the object form thus developing the required prehension force. The principle is relatively efficient but positional accuracy is at best moderate.

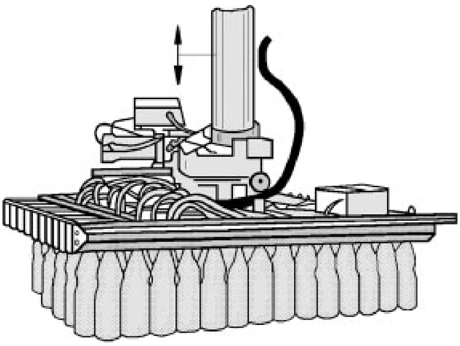
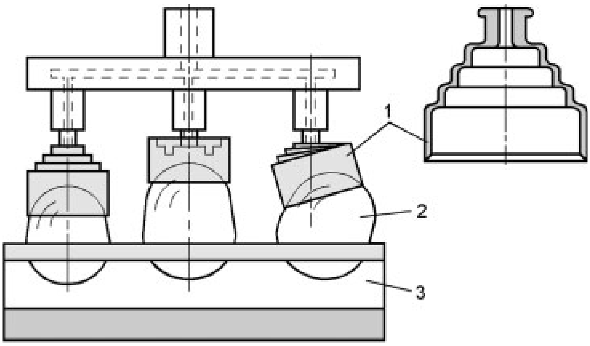


Fig. 14.38: Multiple pneumatic gripper for bottles (*Pronal*)

14.6.3 Multiple Irregular Shaped Objects

Figure 14.39 shows a gripper which is capable of compensating for particularly large differences in height. This allows the serial prehension of relatively light parts (natural products like potatoes or eggs) whose sizes and shapes differ considerably (within certain limits).



1 suction bellows
2 objects
3 magazine

Fig. 14.39: Prehension of eggs

14.7
Prehension of Flexible Objects

14.7.1
Bag and Sack Grippers

There are many products which are packed and shipped in sacks. These can include plastic pellets, grain, powdered chemical products such as fertilizers and building materials etc. Normally presented in a horizontal position on pallets or conveyors, they can be handled using the following prehension techniques (Fig. 14.40):

- Astrictive prehension using vacuum suction. This implies that the surface is leak-proof under vacuum. The suction heads can be designed with a very large areas (low pressure suction heads) in order to avoid selective loading (safety factor of $S = 2.5$ in the prehension force calculations).
- Impactive prehension using plates which grasp from below. The line-shaped contact with the plates ensures stability but for this the sack and its contents must also exhibit some intrinsic stability.
- Impactive prehension using fingers which grasp from below. The fingers are bent for gripping e.g. with a wire cord. However, this method is not suitable for soft foil sacks.
- Holding with forks. This method is especially useful for acquisition from moving conveyor belts.

Figure 14.41 shows the handling of fertilizer sacks which are taken from a roller conveyor and subsequently stacked on pallets. The number of forks depends on the separation of the transport rollers.

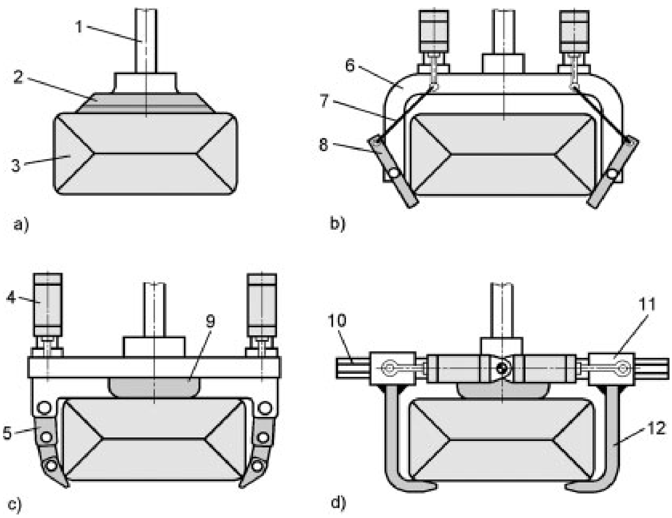
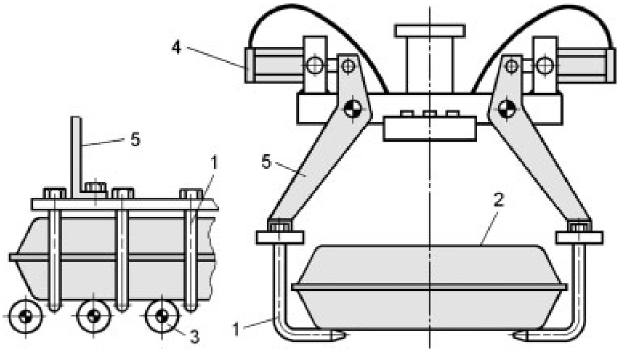


Fig. 14.40: Some practical techniques for sack prehension
a) vacuum suction, b) plates gripping the load from below, c) multi-link fingers, d) forks



1 forks
2 foil sack
3 roller conveyor
4 pneumatic cylinder
5 pivot arm

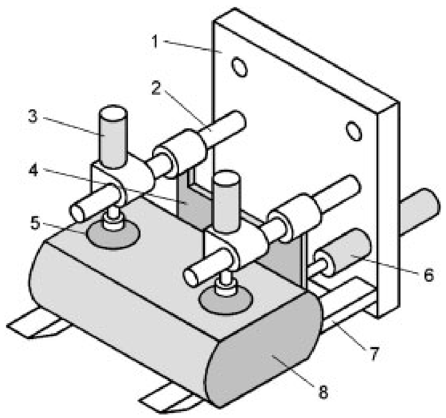
Fig. 14.41: Handling of sacks with a fork gripper

The sack gripper shown in Figure 14.42 also operates with forks. The sack is held by extendable suction caps during motion. The integrated ejection plate can slide the sack from the forks at the intended destination. This is important when the sacks are to be stacked in layers onto pallets.

Figure 14.43 once again shows the principle of the sack gripper from Figure 14.40 b whereas now the support plates (holding claws) are actuated by an electric motor at the point of contact with the object. An electric motor with a rotary to linear translation gear serves as a drive. The force F is implemented over the toggle lever separation and partly compensates for gravitational force $F_G/2$. The following relation is valid:

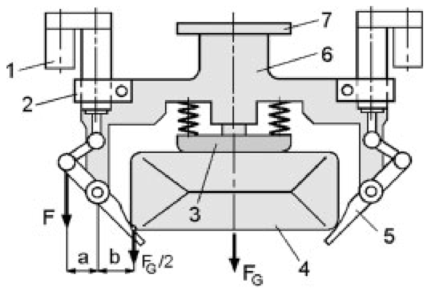
$$F = \frac{F_G \cdot b}{2 \cdot \alpha} \tag{14.1}$$

The electric motors need not produce any driving force once the position for secure object prehension is reached. The load will be held for unlimited time without power consumption by the self-locking of the sliding thread spindle.



1 base plate
2 linear guides
3 pneumatic cylinders
4 ejection plate screen
5 vacuum suction caps
6 pneumatic cylinders
7 gripping fork
8 sack

Fig. 14.42: Sack gripper



1 electric drive
2 holder
3 spring mounted ejection plate
4 object (sack)
5 support plate and claw
6 carrier
7 flange

F force
F_G gravitational force

Fig. 14.43: Sack gripper with electric actuation

14.7.2
Gripping and Mounting of Outside O-rings

An example of the automated mounting of O-rings was briefly introduced at the end of Chapter 12. O-rings are used primarily for pneumatic or hydraulic sealing at an interface between two solid surfaces. They can be loaded with the help of a vibratory bowl feeder or simply randomly presented.

In order to mount an O-ring into a channel, the inner diameter of the ring must first be expanded during mounting to the extent that it is somewhat larger than the outer diameter of the spindle on which the O-ring is presented to the channel. Possible procedures to realize this include e.g. conical mounting sleeves or grippers with many fingers. The grasping organs expand the ring in a polygonal manner as shown in Figure 14.44.

The actual mounting phase can begin after the expansion of the O-ring. It can proceed in a successive manner, section by section, or simultaneously with a single handling device, i.e. the entire perimeter of the O-ring is simultaneously brought into the mounting channel [14-3].

Figure 14.45 shows the design of a 6-point gripper. Two pneumatic cylinders which are independently controlled take over the two tasks, expansion and removal of the O-ring from the gripper, leaving it in the spindle channel. With appropriately designed gripper fingers it is also possible to mount quad-rings, groove-rings, flat sealing rings or rubber

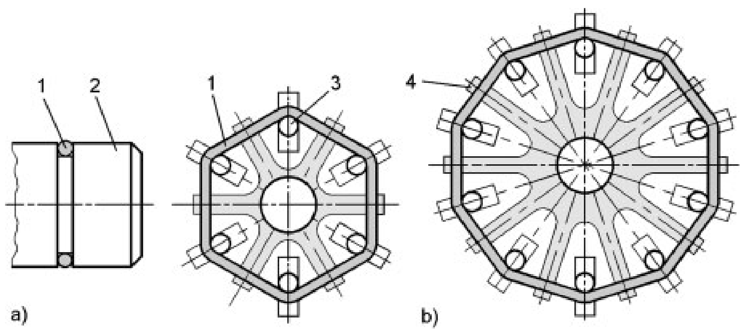


Fig. 14.44: Expansion of O-rings with a gripper
a) 6-point O-ring mounting gripper, b) principle of the 10-point mounting gripper
1 O-ring, 2 spindle, 3 gripper finger, 4 take off jaw

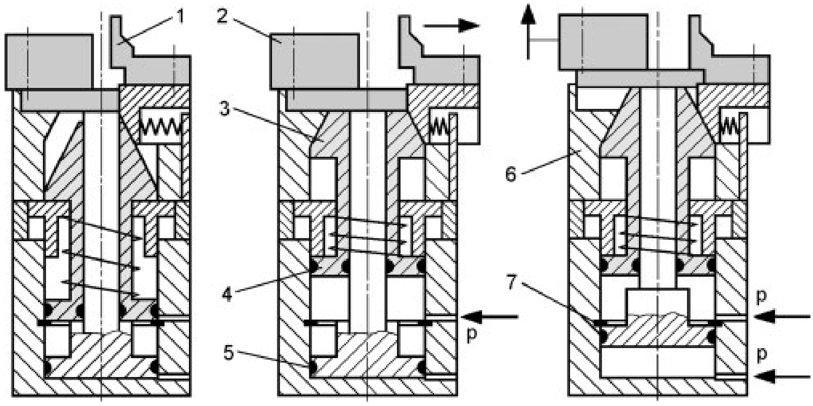
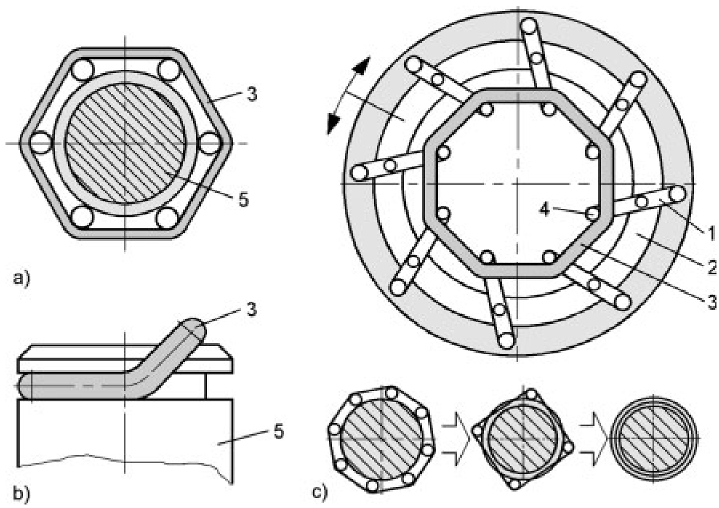


Fig. 14.45: 6-point gripper for mounting of O-rings (after *Sommer-Automatic*)
1 gripper finger, 2 take off jaw, 3 spreading cone, 4 spreading piston, 5 take off piston, 6 housing, 7 stop ring, *p* compressed air

spouts automatically. The adjustable expansion stroke is typically between 3 and 6 mm per finger with gripping forces required for opening as high as 300 N.

Large sealing rings with diameters as large as 150 mm require the use of a 10-point gripper which can develop expansion forces as high as 2000 N with take off strokes of up to 15 mm.

Figure 14.46 a shows once again the polygonal expansion of an O-ring by means of 6 gripper fingers. Removal from the fingers above the channel follows and the O-ring can be rolled into the grove in a similar way to the mounting of a car tire (Fig. 14.46 b).



1 rotatable clamping arm
2 clamping ring
3 O-ring
4 holding pin
5 workpiece

Fig. 14.46: Gripping and expansion of O-rings
a) expansion of the O-ring, b) rolling the O-ring into the grove, c) O-ring prehension using an eight-finger gripper

Figure 14.46 c shows the mounting sequence with an 8-finger gripper. The fingers are pulled back in two steps. Initially only 4 fingers are drawn back and the O-ring sits at 4 points in the channel. Then the remaining 4 fingers are pulled back so that the O-ring remains completely in the work surface channel.

14.8 Medical Applications

Although artificial hands in the form of protheses have been around since very early times (see Section 1.4), robot grippers used in medicine and surgery form a small niche area that has slowly developed over the past twenty years. A number of the smaller devices have already been mentioned in Chapter 7. This final section provides a brief overview together with some interesting research results.

The history of robotics in surgery is punctuated with spectacular successes and, often more publicised, failures. In almost all cases the failures have been largely the result of the wrong choice of robot. A possible example is the "RoboDoc" [14-4] project in which a SCARA (cylindrical work envelope) robot was used for tasks which would have been better carried out using a fully articulated 6-axis (spherical work envelope) robot. On the other hand this problem was avoided in the REPOROBO project from the outset [14-5]. Often the lack of dexterity of the gripper is blamed when in reality the manipulator is inadequate or the gripper fingers lack the necessary proportional control [14-6].

The vast majority of robot grippers used in surgery are impactive. In many microsurgery applications they come into direct contact with organs, tissue, arteries etc. On a larger scale, for example in accident surgery and bone repositioning applications, it is the fixtures which are held by robot rather than the patient directly.

An excellent example is in a typical femur or humerus fracture where the two ends of the break must be precisely repositioned and secured for a period of time. Conventionally, two stainless steel pins are bored through the flesh and into the bones at both sides of the fracture. These are then connected together by means of carbon fibre rods. Now both these fixtures must be moved relative to one another in order to precisely reposition the two bone segments.

As can be imagined, working against the elasticity of tissue and contracted muscle, this requires a degree of physical strength from the medical personnel involved. Measurements on live patients have revealed forces of up to a maximum of 300 Newton may be required, which is also the plastic deformation limit for the pins [14-7]. Unfortunately, manual repositioning errors of up to 20° have been reported in the literature [14-8 to 14-10]. This factor alone provides a very good motivation for the potential use of robots.

After repositioning of the two bone segments both fixtures are connected together by a third rod as shown in Figure 14.47. After this, securing is completed by the insertion of a long stainless steel spline through the marrow channel in the bone.

In a robotic system, either one of the fixtures must be immobilized by securing it to the operating table or movement sensors must provide the necessary kinematic data to enable the robot to follow the movements of the patient. The robot must then manipulate the sec-

Fig. 14.47: Typical fixture after fracture repositioning

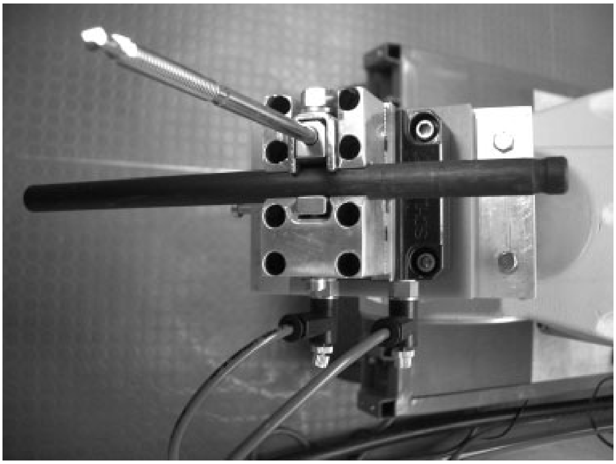


Fig. 14.48: Gripper designed for prehension at fixture intersection

ond fixture in order to bring the two ends of the fracture precisely together to within a fraction of a degree [14-11].

Because of problems associated with potential post-prehension slippage it is necessary to grip directly at the intersection between the carbon fibre rods and the stainless steel pins in order to guarantee stable prehension.

As can be seen from Figure 14.48, the carbon fibre rod, stainless steel pin and the connecting clamp all run orthogonal to one another. This is used to advantage by machining the gripper fingers to ensure a tight fit thus eliminating any danger of slippage. The price is a higher demand on the robots ability to accurately position the endeffector – a factor which falls well within the capabilities of most modern industrial robots. The basic gripper module used in the configuration of Figure 14.48 is a pneumatically driven *Schunk* KSP64, with low play similar to that shown in Figure 3.49, capable of a 2500 Newton clamping force [14-12].

A force-torque sensor of the type discussed in Chapter 11 is situated between the robot gripper and wrist. This gives warning of large forces and torques should they start to approach the allowed limits. Should it not be possible (for whatever reason) to immobilize one of the fixtures by securing it to the operating table then any movements of the anesthetised patient during the operation must be compensated for by movement of the robot. Consequently, the robot must be capable of following such small movements in real-time. For this reason some form of navigation system is needed. Acoustic, infra-red and camera systems all have a common problem in that their area of measurement may suddenly be obscured by personell or equipment. Experiments with tilt sensors mounted directly to one side of the fracture have shown far more promising results in this respect [14-11].

Though many very intrusive tools are commonly used in surgery, few truly ingressive grippers are relevant. Exceptions include needle based systems, one example of which has been proposed for use in eye surgery [14-13]. However, much research work remains to be done in this direction before any commercially available devices are likely to reach the operating theatre.

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