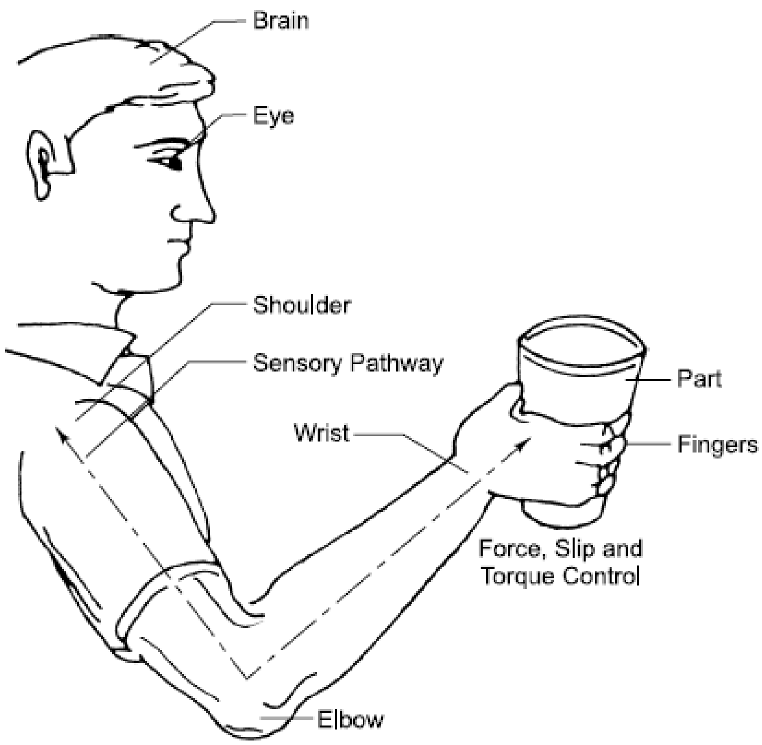
4. Robot End-Effectors

4.1. INTRODUCTION

The robot end-effector or end-of-arm tooling is the bridge between the robot arm and the environment around it. Depending on the task, the actions of the gripper vary. What is the ideal gripper? Should it be like a human hand with fingers that have 22 degrees of freedom? The most striking thing about the human hand is that it can adapt to the task as it is a sensory and communicating organ. A human being decides the global position of his hand based on the analysis of his eye and memory and then determines his choice of grip and the necessary manipulation with the aid of sensors on his skin, arm and wrist (Fig. 4.1).

Figure 4.1 Choice of grip



A robotic end-effector which is attached to the wrist of the robot arm is a device that enables the general-purpose robot to grip materials, parts and tools to perform a specific task. The end-effectors are also called the grippers. There are various types of end-effectors to perform the different work functions. The various types of grippers can be divided into the following major categories:

- Mechanical grippers
- Hooking or lifting grippers
- Grippers for scooping or ladling powders or molten metals or plastics
- Vacuum cups
- Magnetic grippers
- Others: Adhesive or electrostatic grippers.

The grippers may be classified into:

- Part handling grippers
- Tools handling grippers and
- Special grippers

The part handling grippers are used to grasp and hold objects that are required to be transported from one point to another or placed for some assembly operations. The part handling applications include machine loading and unloading, picking parts from a conveyor and moving parts, etc.

There are grippers to hold tools like welding gun or spray painting gun to perform a specific task. The robot hand may hold a deburring tool.

The grippers of the robot may be specialized devices like Remote Centre Compliance (RCC) to insert an external mating component into an internal member, viz. inserting a plug into a hole.

The other types of end-effectors employ some physical principle like magnetism or vacuum technology to hold the object securely.

4.2. CLASSIFICATION OF END-EFFECTORS

An end-effector of a robot can be designed to have several fingers, joints and degrees of freedom. Any combination of these factors give different grasping modalities to the end-effector.

The general end-effectors can be grouped according to the type of grasping modality as follows:

- Mechanical fingers
- Special tools
- Universal fingers

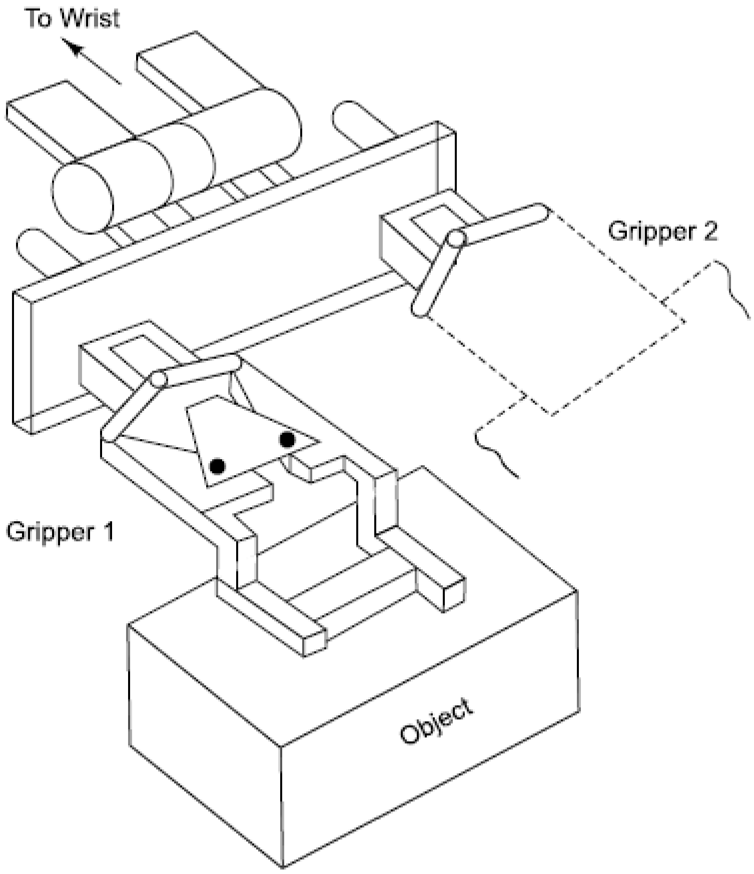
Mechanical fingers are used to perform some special tasks. Gripping by mechanical type fingers is less versatile and less dextrous than holding by universal fingers as the grippers with mechanical fingers have fewer number of joints and lesser flexibility. However, they economize the device cost.

The grippers can be subgrouped according to finger classifications, for example, the number of fingers, typically two-, three-, and five-finger types. The two-finger gripper is the most popular.

Another classification is according to the single gripper and multiple grippers mounted on the wrist.

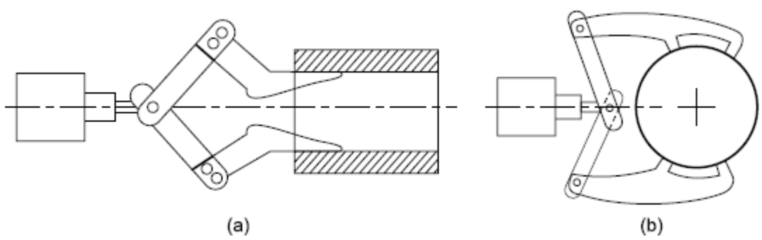
Multigripper systems shown in Fig. 4.2 enable effective simultaneous execution of more than two different jobs. Design methods for each individual gripper in a multigripper system are subject to those of single grippers.

Figure 4.2 Multiple grippers



Robot end-effectors can be classified on the basis of the mode of gripping as external and internal gripping. The internal gripping system shown in Fig. 4.3(a) grips the internal surface of objects with open fingers whereas the external gripper shown in Fig. 4.3(b) grips the exterior surface of objects with closed fingers.

Figure 4.3 Internal and external grippers (a) Internal gripper (b) External gripper



Robot end-effectors are also classified according to the number of degrees of freedom (DOF) incorporated in the gripper structures. Typical mechanical grippers belong to the class of 1 DOF. A few grippers can be found with more than two DOFs.

Using some special tooling action, robot grippers can be designed to retain objects by electromagnetic action or under the action of vacuum. Electromagnets and vacuum cups are typical devices in this class. Usually, if the objects to be handled are too large and ferromagnetic in nature, electromagnetic grippers may be employed. In some applications where the objects are too thin to be handled, they can be held by vacuum grippers.

Universal fingers usually comprise multipurpose grippers of more than three fingers and or more than one joint on each finger which provide the capacity to perform a wide variety of grasping and manipulating assignments.

4.3. DRIVE SYSTEM FOR GRIPPERS

In typical robot gripper systems, there are three kinds of drive methods:

- Electric
- Pneumatic
- Hydraulic

In electric drive system, there are typically two kinds of actuators, dc motors and stepper motors. In general, each motor requires appropriate reduction gear systems to provide proper output force or torque. In the electric system, a servo power amplifier is also needed to provide a complete actuation system.

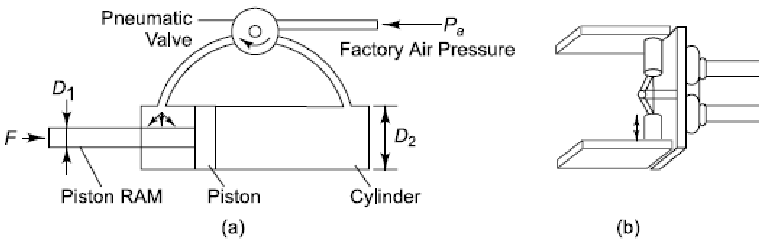
The pneumatic system has the merit of being less expensive than other methods, which is the main reason for it being used in most of the industrial robots. Another advantage of the pneumatic system is the low-degree of stiffness of the air-drive system. This feature of the pneumatic system can be used effectively to achieve compliant grasping which is necessary for one of the most important functions of grippers; to grasp objects with delicate surfaces carefully. On the other hand, the relatively limited stiffness of the system makes precise control difficult.

Hydraulic drives used in robot gripping systems are usually electrohydraulic drive systems. They have almost the same configuration as pneumatic systems, though their features are different from each other. A typical hydraulic drive system consists of actuators, control valves and power units. There are three kinds of actuators in the system: piston cylinder, swing motor, and hydraulic motor. To achieve positional control using electric signals electrohydraulic conversion drives are used.

4.3.1.1. Designing Piston-Cylinder in the Pneumatic Gripper

The gripper shown in Fig. 4.4 is used for holding cartons. A piston which can supply the actuating force F may be chosen. It is logical to orient the piston device in the gripper such that this force is supplied on the extension stroke of the piston.

Figure 4.4 Pneumatic gripper for handling cartons (a) Drive system (b) Gripper for cartons



Suppose the factory air pressure is P_a. It is necessary to determine the required diameter of the piston in order to provide the desired actuating force, F.

Now,

$$F = P_a \times \frac{\pi D_2^2}{4}$$

where D_2 = Piston diameter, mm

P_a = supply pressure, kgf/mm^2

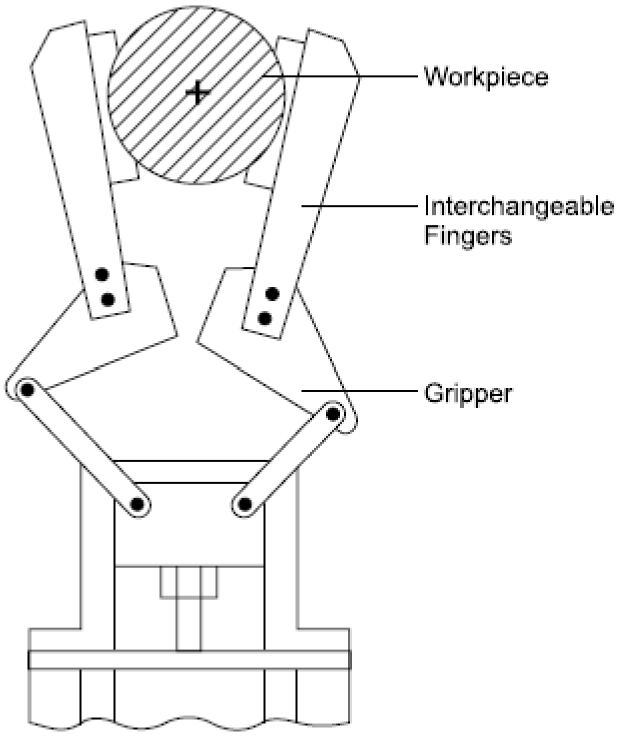
or,

$$D_2 = \sqrt{\frac{4 \times F}{\pi P_a}}$$

4.4. MECHANICAL GRIPPERS

A mechanical gripper is an end-effector that uses mechanical fingers actuated by a mechanism to grip an object. The fingers are the appendages of the gripper that actually makes contact with the object. The fingers are either attached to the mechanism or are an integral part of the mechanism. The use of replaceable fingers allows for wear and interchangeability. Differents sets of fingers for use with the same gripper mechanism can be designed to accommodate different parts models. A gripper with interchangeable fingers is shown in Fig. 4.5.

Figure 4.5 Mechanical gripper with interchangeable fingers



Several kinds of gripper functions can be realized using various mechanisms. From observations of the usable pair elements in the gripping device, the following kinds are identified: (i) linkage (ii) gear-and-rack (iii) cam, (iv) screw (v) cable and pulley and so on. The selection of these mechanisms is influenced by the kind of actuators to be employed and the kind of grasping modality to be used.

Another method of classifying the mechanical grippers is according to the type of finger movement used by the gripper. In this classification, the grippers can actuate the opening or closing of the fingers by one of the following motions:

- Pivoting or swinging movement
- Linear or translational movement

In most applications, two fingers are sufficient to hold the workpiece. Grippers with three or more fingers are less common.

4.4.1. Mechanical Grippers with Two Fingers

4.4.1.1. Pivoting or Swinging Gripper Mechanisms

This is the most popular mechanical gripper for industrial robots. It can be designed for limited shapes of an object, especially cylindrical workpiece. If actuators that produce linear movement are used, like pneumatic piston-cylinders, the device contains a pair of slider-crank mechanisms.

In the slider crank mechanism shown in Fig. 4.6, when the piston 1 is pushed by pneumatic pressure to the right, the elements in the cranks 2 and 3, rotate counter clockwise with the fulcrum F_1 and clockwise with the fulcrum F_2 respectively, when θ < 180°. These rotations make the grasping action at the extended end of the crank elements 2 and 3. The releasing action can be obtained by moving the piston to the left. An angle θ ranging from 160° to 170° is commonly used.

Figure 4.6 Schematic diagram of a gripper using slider-crank mechanism

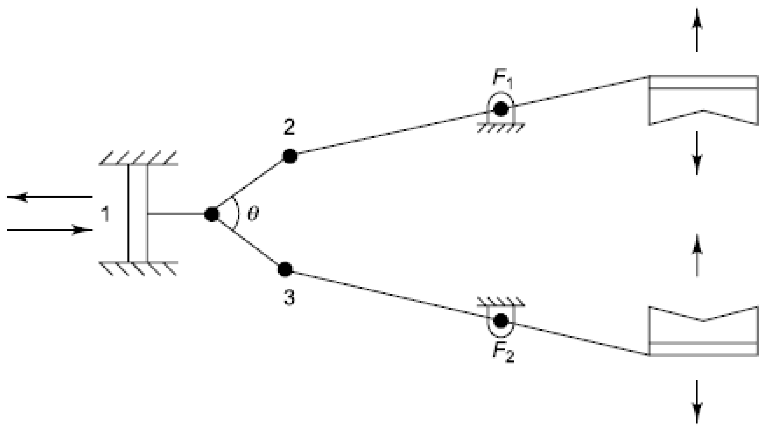


Figure 4.7 is another example of swinging gripper that uses the piston-cylinder. This is the swing-block mechanism. The sliding rod 1, actuated by the pneumatic piston transmits motion by way of the two symmetrically arranged swing-block linkages 1–2–3–4 and I–2–3'–4' to grasp or release the object by means of the subsequent swinging motions of links 4 and 4' at their pivots F_1 and F_2.

Figure 4.7 Schematic diagram of a gripper using swing block mechanism

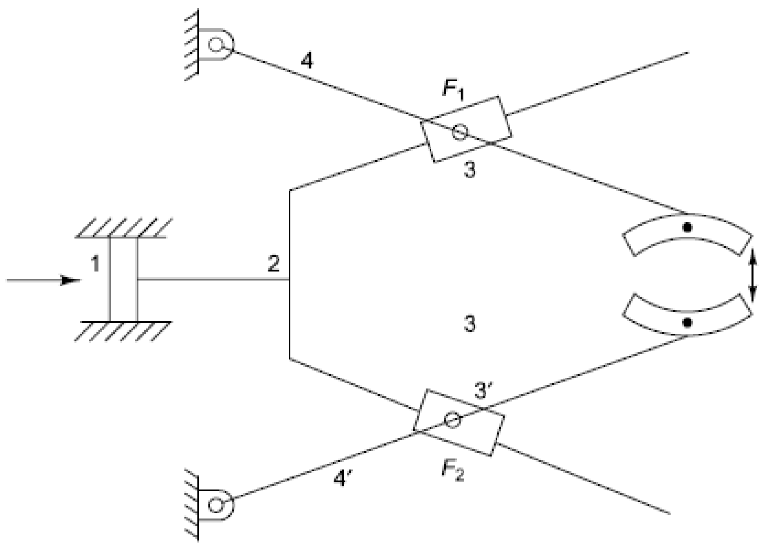
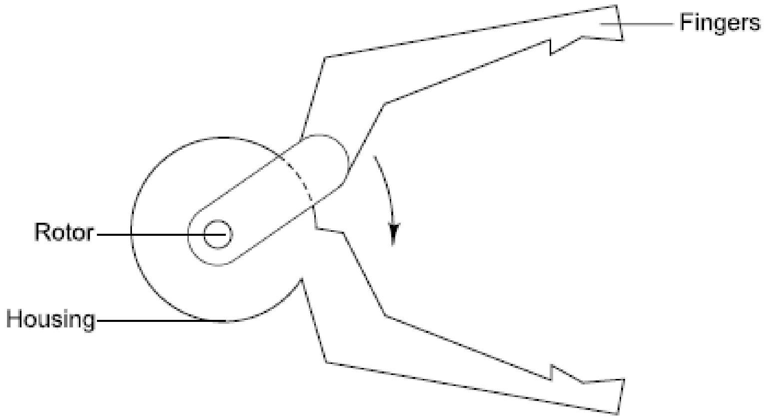


Figure 4.8 illustrates a typical example of a gripper using a rotary actuator in which the actuator is placed at the cross point of the two fingers. Each finger is connected to the rotor and the housing of the actuator, respectively. The actuator movement directly produces grasping and releasing actions.

Figure 4.8 Gripper with a rotary actuator



The cam actuated gripper includes a variety of possible designs, one of which is shown inFig. 4.9. A cam and follower arrangement, often using a spring-loaded follower, can provide the opening and closing action of the gripper. The advantage of this arrangement is that the spring action would accommodate different sized objects.

Figure 4.9 Cam actuated gripper

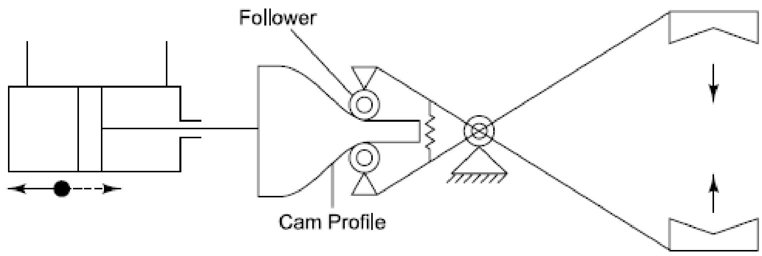
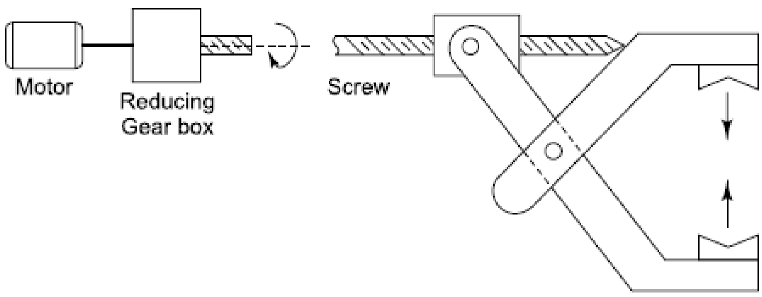


Figure 4.10 indicates an example of screw-type actuation used in the gripper design. The screw is turned by a motor, usually accompanied by a speed reduction mechanism. Due to the rotation of the screw, the threaded block moves, causing the opening and closing of the fingers depending on the direction of rotation of the screw.

Figure 4.10 Screw type gripper



4.4.1.2. Translation Gripper Mechanisms

Translational mechanisms are widely used in grippers of industrial robots. The simplest translational gripper uses the direct motion of the piston cylinder, shown in Fig. 4.11. The finger motion corresponds to the piston movement without any connecting mechanisms between them. The drawback is that sometimes it is difficult to design the desired size of the gripper, because here the actuator size decides the gripper size.

Figure 4.11 Translational gripper using cylinder piston

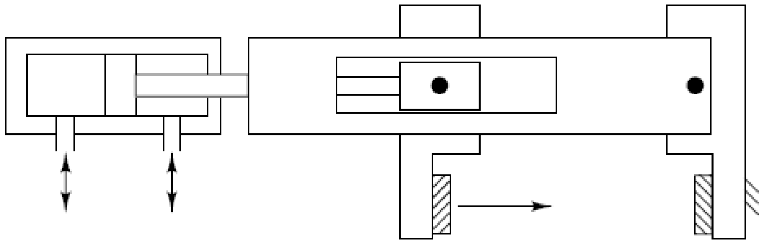
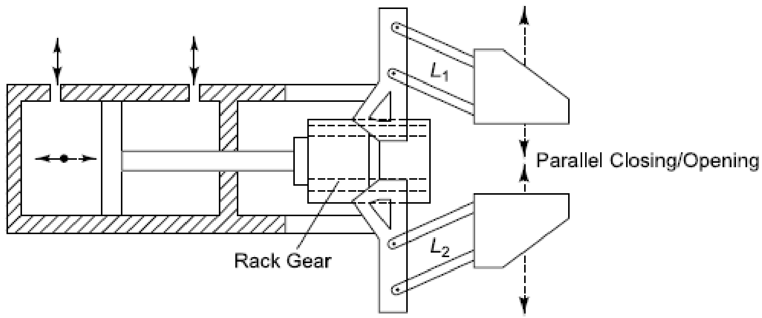


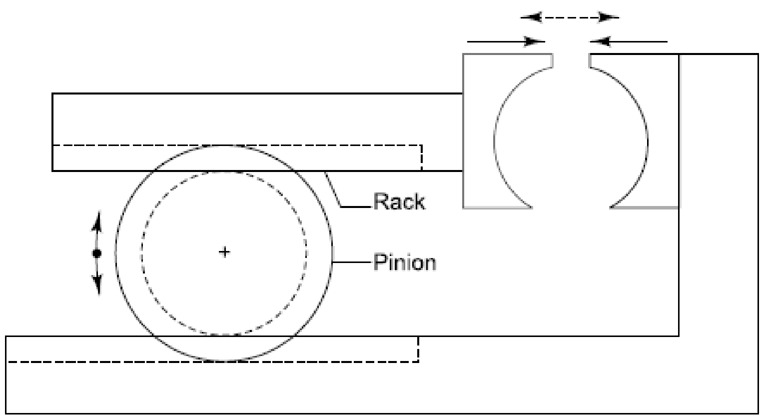
Figure 4.12 shows a translational gripper using a hydraulic or pneumatic piston-cylinder, which includes a dual-rack gear mechanism and two pairs of symmetrically arranged parallel closing linkages. The pinion and sector gears are connected to the elements L_1 and L_2 respectively. When the piston rod moves towards left, the translation of the rack causes the two pinions to rotate clockwise and anticlockwise respectively and produces the grasping action, keeping each finger direction constant. The release action occurs when the piston rod moves to the right in the same way.

Figure 4.12 Translational gripper using parallel bar linkages



Rotary actuators can also be used for translational gripper mechanisms as shown inFig. 4.13.

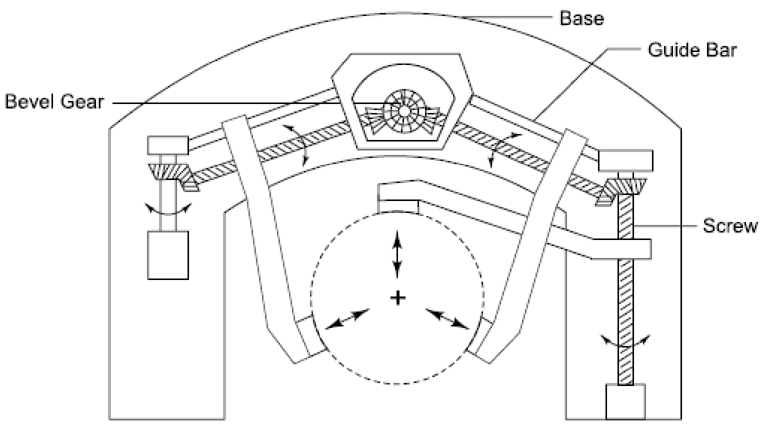
Figure 4.13 Translational gripper using rotary actuators



4.4.2. Mechanical Grippers with Three Fingers

The increase of the number of fingers and degrees of freedom will greatly aid the versatility of grippers. The main reason for using the three-finger gripper is its capability of grasping the object in three spots, enabling both a tighter grip and the holding of spherical objects of different size keeping the centre of the object at a specified position. Three point chuck mechanisms are typically used for this purpose. Figure 4.14 gives an example of this gripper. Each finger motion is performed using ball-screw mechanism. Electric motor output is transmitted to the screws attached to each finger through bevel gear trains which rotate the screws. When each screw is rotated clockwise or anticlockwise, the translational motion of each finger will be produced, which results in the grasping-releasing action.

Figure 4.14 Gripper using three point chuck mechanism



4.5. MAGNETIC GRIPPERS

Magnetic grippers are used extensively on ferrous materials. In general, magnetic grippers offer the following advantages in robotic handling operations:

1. Variations in part size can be tolerated
2. Pickup times are very fast
3. They have ability to handle metal parts with holes
4. Only one surface is required for gripping

The residual magnetism remaining in the workpiece may cause problems. Another potential disadvantage is the problem of picking up one sheet at a time from a stack. The magnetic attraction tends to penetrate beyond the top sheet in the stack, resulting in the possibility that more than a single sheet will be lifted by the magnet.

Magnetic grippers shown in Fig. 4.15 can use either electromagnets or permanent magnets. Electromagnetic grippers [Fig. 4.15 (b)] are easier to control, but require a source of dc power and an appropriate controller. When the part is to be released, the control unit reverses the polarity at a reduced power level before switching off the electromagnet. This procedure acts to cancel the residual magnetism in the workpiece ensuring a positive release of the part. The attractive force, *P* of an electromagnet is found from Maxwell's equation given by

$$P = \frac{(IN)^2}{25A_c(R_a + R_m)}$$

where

IN = Number of amp-turns of coil

A_c = Area of contact of an object with magnet

R_a, R_m = Reluctances of magnetic paths through air and metal respectively

$$P \geq (a + g)m \times FS$$

where

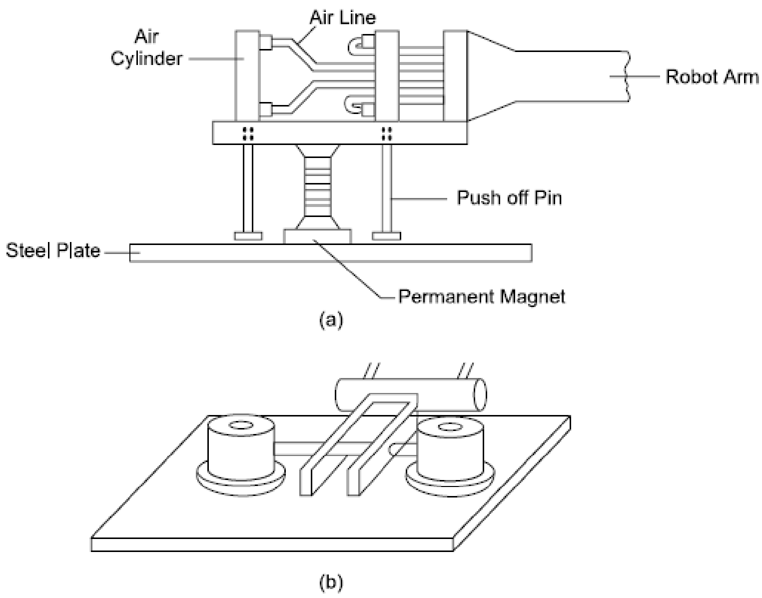
a = gripper acceleration

g = gravitational constant

m = mass and *FS* = Factor of safety

Permanent magnets do not require an external power and hence they can be used in hazardous and explosive environments, because there is no danger of sparks which might cause ignition in such environments. When the part is to be released at the end of the handling cycle, in case of permanent magnet grippers, some means of separating the part from the magnet must be provided. One such stripping device is shown in Fig. 4.15(a).

Figure 4.15 Magnetic grippers (a) Permanent magnet type (b) Electromagnet type

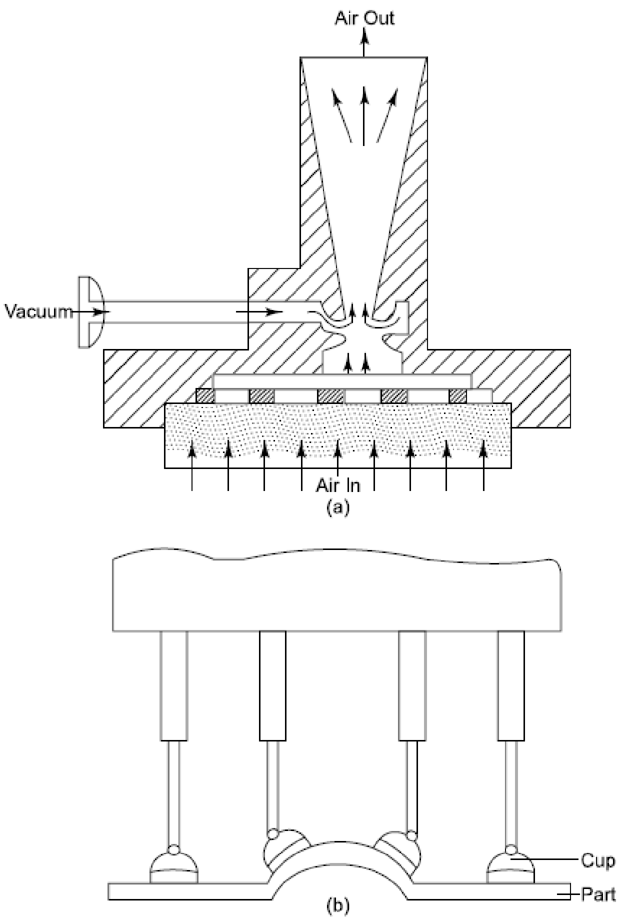


4.6. VACUUM GRIPPERS

Large flat objects are often difficult to grasp. One solution to this problem is the use of vacuum gripper. Vacuum grippers are used for picking up metal plates, pans of glass, or large lightweight boxes. Since the vacuum cups are made of elastic materials, they are complaint. The gripper is tolerant of errors in the orientation of the part and is especially suited for pick-and-place work. For handling softer materials, cups made of harder material are used.

A typical vacuum cup gripper is shown inFig. 4.16(a). It is used extensively for lifting fragile materials. A compressed air supply and a venturi are used to create a gentle vacuum that lifts the part.

Figure 4.16 Vacuum gripper (a) Ventury device for flat surface gripping (b) Gripper for contoured surface



The lift capacity of the suction cup [Fig. 4.16(b)] depends on the effective area of the cup and the negative air pressure between the cup and the object. The relationship can be shown by the equation:

$$F = KPA_c = KA_c\,(P_a - P_{res})$$

where

F = force or lift capacity, N

P = negative pressure, N/cm^2

A_c = total effective area of the suction cup(s) used to create the vacuum, cm^2

K = a coefficient depending on atmospheric pressure and conditions of seal

p_a = the atmospheric pressure and

p_{res} = residual pressure in vacuum-cup.

The negative air pressure is the pressure differential between the inside and the outside of the vacuum cup.

Instead of a venturi, a vacuum pump powered by an electrical motor may also be used.

4.7. ADHESIVE GRIPPERS

An adhesive substance can be used for grasping action in gripper design. The requirement on the items to be handled are that they must be gripped on one side only. The reliability of this gripping device is diminished with each successive operation cycle as the adhesive substance loses its tackiness on repeated use. To overcome this limitation, the adhesive material can be loaded in the form of a continuous ribbon into a feeding mechanism attached to the robot wrist.

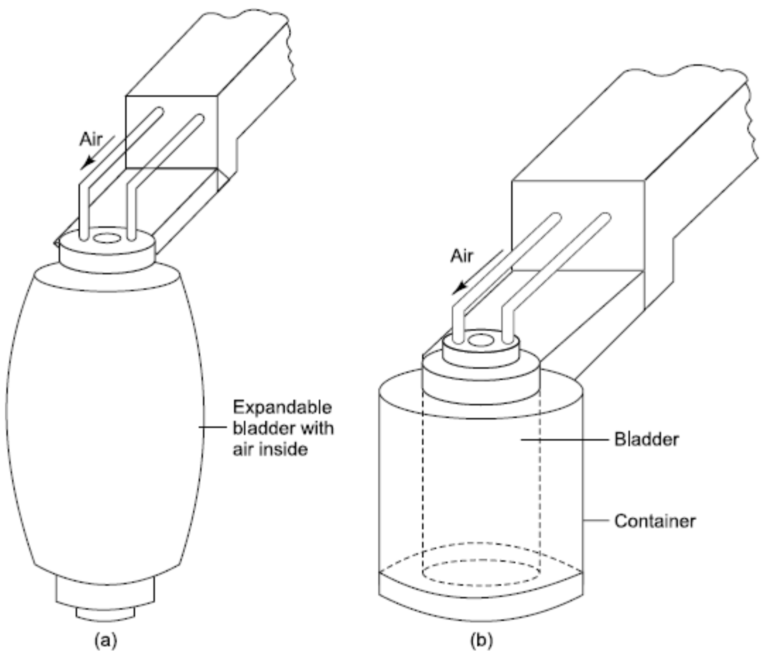
4.8. HOOKS, SCOOPS AND OTHER MISCELLANEOUS DEVICES

Hooks can be used as end-effectors to handle containers and to load and unload parts hanging from overhead conveyors. The item to be handled by a hook must have some sort of handle to enable the hook to hold it.

Ladles and scoops can be used to handle certain materials in liquid or powder form. One of the limitations is that the amount of material being scooped by the robot is sometimes difficult to control.

Other types of grippers include inflatable devices, in which an inflatable bladder is expanded to grasp the object. The inflatable bladder is fabricated out of some elastic material like rubber, which makes it appropriate for gripping fragile objects. In contrast to the typical mechanical grippers where a concentrated force is applied on the object, the gripper applies a uniform grasping pressure against the surface of the object. An example of this type of gripper is shown in Figs 4.17(a) and (b).

Figure 4.17 Expanding bladder for gripping internal surface (a) Bladder fully expanded (b) Bladder inside the container

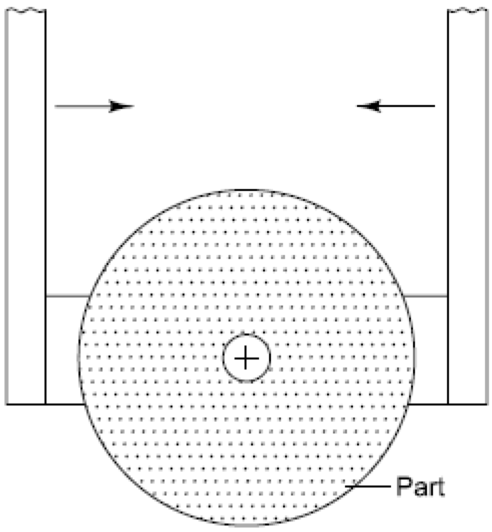


4.9. GRIPPER FORCE ANALYSIS AND GRIPPER DESIGN

The purpose of the gripper mechanism is to convert input power into the required motion and force to grasp and retain an object. So the gripping force required must be calculated first. When the gripping force is established, the required actuator force or torque can be computed for a given gripper design.

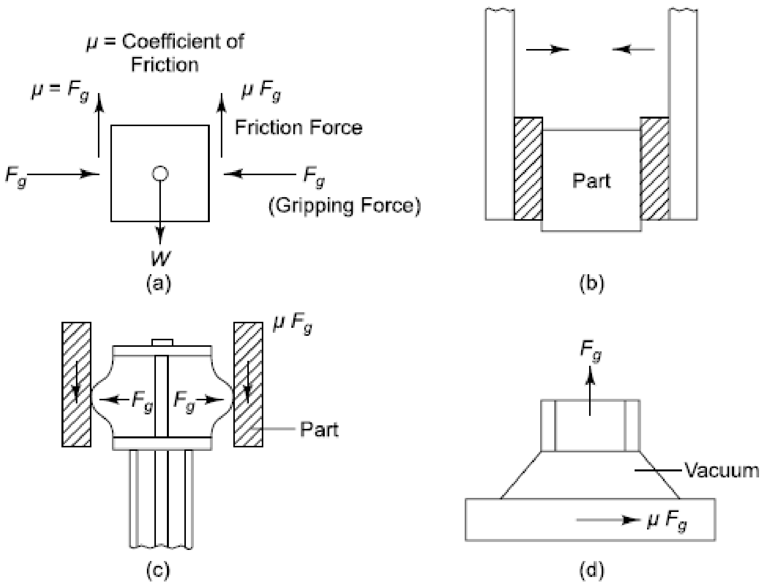
There are two ways of constraining the part in the gripper. In the first way, the gripper fingers may enclose the part to some extent, thereby constraining the motion of the part. This is accomplished by designing the contacting surface of the fingers to be in the approximate shape of the part geometry as shown in Fig. 4.18. The second way of holding the part is by friction between the fingers and the object. In this approach, the fingers must apply a force that is sufficient for friction to retain the part against gravity, acceleration and any other force that might arise during the holding portion of the working cycle.

Figure 4.18 Gripper enclosing partly the envelope of a part



The friction method of holding the parts results in a less complicated and therefore less expensive gripper design and it tends to be readily adaptable to a greater variety of workparts. However there is a problem with the friction method that is avoided with the physical constriction method. If a force of insufficient magnitude is applied against the part in a direction parallel to the friction surfaces of the fingers as shown in Fig. 4.19, the part might slip out of the gripper. To resist this slippage, the gripper must be designed to exert a force that depends on the weight of the part, the coefficient of friction between the part surface and the finger surface, the acceleration of the part and the orientation of the direction of motion during acceleration with respect to the direction of the fingers. This may be demonstrated through the analysis of several examples given below.

Figure 4.19 Gripping mechanism working with mechanical friction (a) Free-body diagram (b) Friction in mechanical gripping (c) Friction in plug type gripper (d) Friction in suction gripper



Example 4.1 Consider the gripper and load illustrated in Fig. 4.20(a). The gripping surface applies a force F_g along an axis that passes right through the centre of gravity of the load, in this case a rectangular block. Figure 4.20(b) shows the cube at

different orientations in gripping condition. The force that must be applied to prevent slippage due to gravity depends on two things:

1. The angle, θ that the gripping surface subtends to the horizontal.
2. The coefficient of friction, μ between the gripping surface and the load surface.

The gripping force that must be applied is

$$F_g = \frac{mg\sin\theta}{\mu n}$$

where

m = mass, kg

g = acceleration due to gravity, m/s^2

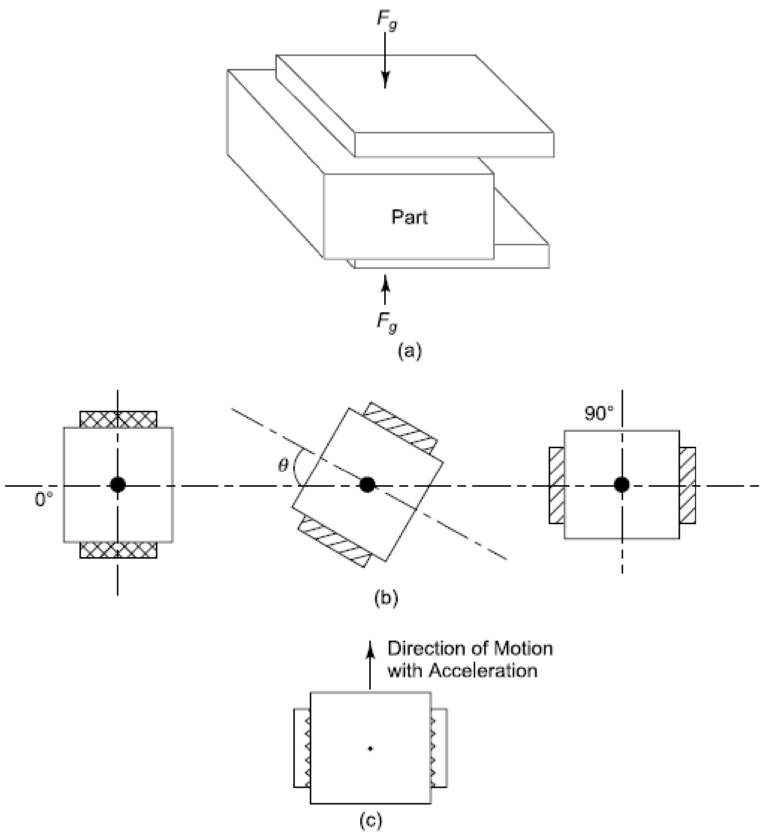
μ = coefficient of friction

θ = angle subtended with the horizontal

n = number of pairs of contact surfaces

When this force has been determined, it represents only the static force. The static force is the minimum force that must be applied to the stationary load. When the load moves, it accelerates up to some designated operating speed. The worst case would be if it had to move vertically upwards as illustrated in Fig. 4.20(c).

Figure 4.20 Gripping the rectangular block (a) Forces acting (b) A cube in different orientations during gripping (c) Gripping when the object Is moving vertically



Example 4.2 A 5 kg rectangular block is gripped in the middle and lifted vertically at a velocity 1 m/s. If it accelerates to this velocity at 27.5 m/s^2 and the coefficient of friction between the gripping pads and the block is 0.48, calculate the minimum force that would prevent slippage.

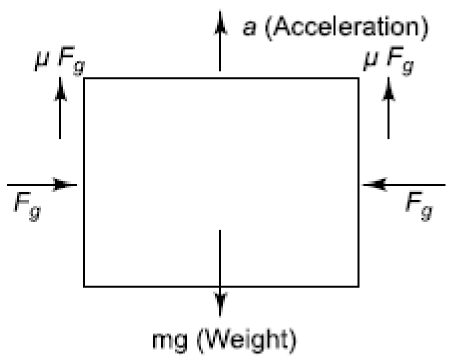
Considering the free body diagram (Fig. 4.21)

$$2\,\mu\,F_g - mg = ma \qquad \text{[considering two fingers]}$$

where *a* is the acceleration upward or,

$$F_g = \frac{m(a+g)}{2\mu} = \frac{5(27.5+9.8)}{2\times 0.48} = 194.1 \text{ N}$$

Figure 4.21 Figure of example problem 4.2

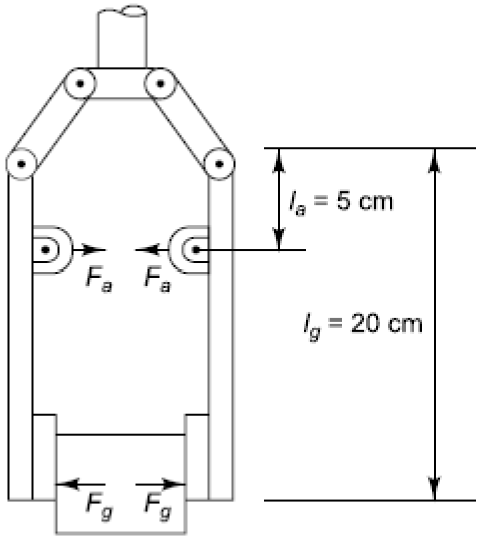


This is the minimum amount of force. To be absolutely sure of lifting the block without slippage, a safety factor should be introduced.

The following example illustrates the analysis that may be used to determine the magnitude of the actuator force and the required input power in order to obtain a given gripping force. For this analysis, it is assumed that a friction type grasping action is being used to hold the part.

Example 4.3 A simple pivot-type gripper is used to hold boxes as illustrated in Fig. 4.22. The gripping force, F_g required is 20 kgf. The gripper is to be actuated by a piston device to apply an actuating force, F_a. The corresponding lever arms for the two forces are shown in the diagram.

Figure 4.22 *Pivot type gripper of example problem 4.3*



Taking moments of the forces on one arm and summing them to zero, we get,

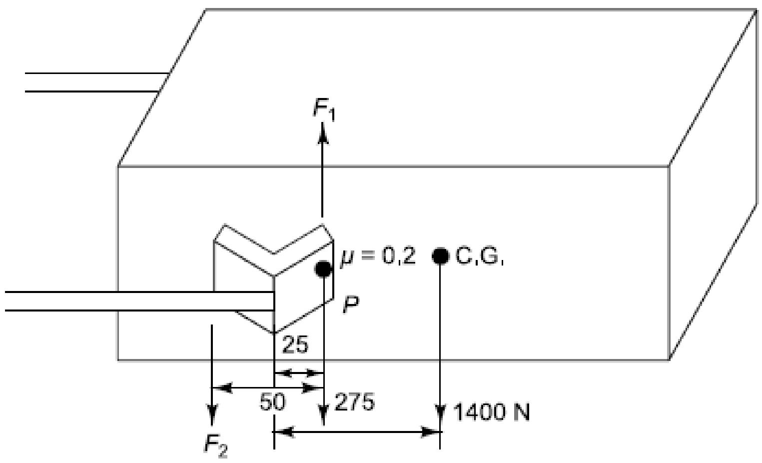
$$F_g L_g = F_a l_a$$

$$\text{or,} \quad F_a = \frac{F_g l_g}{l_a} = \frac{20 \times 20}{5} = 80 \text{ kgf}$$

Therefore, the piston device would have to provide an actuating force of 80 kgf to close the gripper with a force against the boxes of 20 kgf.

Example 4.4 A block of weight having 1400 N is to be gripped as shown in Fig. 4.23. Find the clamping force assuming a safety factor of 2. Assume coefficient of friction μ = 0.2. The centre of gripping does not coincide with the centre of gravity.

Figure 4.23 *Figure of example problem 4.4*



Assuming acceleration $a \uparrow$ upward,

Resolving vertical forces $1400 + 2F_2 = 2F_1 - \dfrac{W_a}{g}$

Resolving moments about P, $50\ F_2 = (1400 \times 250)/2$

or,

$$F_2 = \frac{1400 \times 250}{50 \times 2} = 3500 \text{ N}$$

Therefore,

$$F_1 = 5600 \text{ N [assume } a = 2 \text{ g]}$$

$$\text{Clamping force} = \frac{(F_1 + F_2) \times \text{safety factor}}{\mu}$$

$$= \frac{9100 \times 2}{0.2} \text{N}$$

$$= 91000 \text{ N}$$

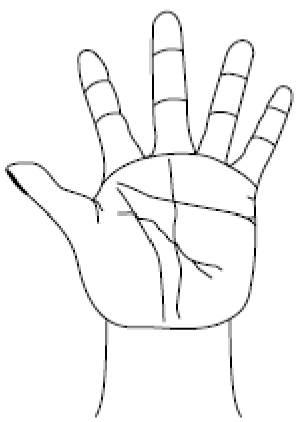
This is greater than the value for gripping at the C.G. If the block is to be lifted by holding it at the C.G. of the block, the gripping force will be less.

4.10. DESIGN OF MULTIPLE DEGREES OF FREEDOM INSTRUMENTED ROBOT HAND

The key element of a robot is its gripper system, which can accommodate a variety of work pieces. Robot gripper comprises rigid links and has, in general, one degree of mobility. Two-finger grippers sometimes of lever type, cam type, gear type or mixed type are very common for many industrial applications. However, multiple degrees of freedom dexterous robot fingers make a better choice to be used as reliable gripping device with predicted outcome of human hand capability. The human hand with its entire neural controller is one of the best structures of the gripping device that can respond precisely and objectively. The beauty of the human finger lies in its complex anatomy, internal structure of the hand and its neural controller that provides grasping attributes like sensitivity, precision, dexterity, stability and security.

When the functionality of human hand shown in Fig. 4.24 is mapped into dexterous multi-degrees of freedom robot hand, the robotic hand like human hand may have the thumb, index finger, middle finger, ring finger and the palm.

Figure 4.24 Human hand



Design of a multi-degrees of freedom dexterous hand with index, middle, ring finger and a thumb, all located on the palm is described in this section. The fingers along with the thumb are actuated by electric motors through mechanical tendons and linkages. The hand with the forearm has also been given a roll motion.

The issues that dictate the design of the multiple degrees of freedom robotic gripper are as follows:

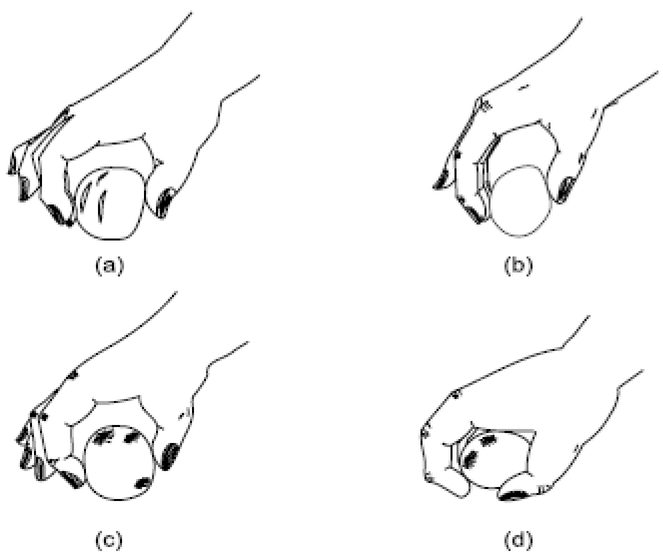
1. Geometry of the object to be gripped and the choice of grip,
2. Task requirements involving kinematics, slippage, compliance and dynamics.

In the choice of gripping, the most important issues are:

1. Power for security and stability,
2. Dexterity for security and sensitivity.

When the object is gripped or wrapped with the aids of the thumb and other fingers along with the palm in which the object is supported or located, the grip is known as 'power grip', shown in Fig. 4.25(d) and when the object is gripped between thumb and other fingers without any support from the palm, the grip is 'dexterous and sensitive' shown in Figs 4.25(a, b, c).

Figure 4.25 Different gripping strategies for the power and sensitive grip



4.10.1. Design of Two Fingers and Multi Fingers Robot Hand

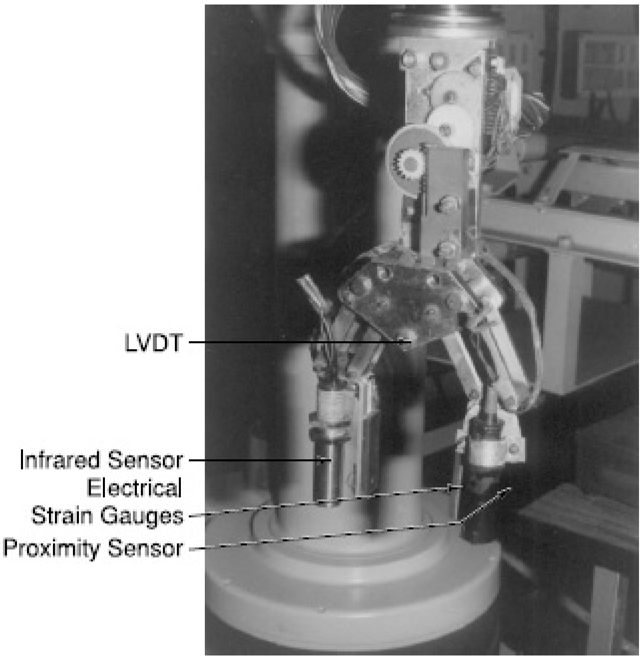
Three-design schemes are described. They are:

1. Two fingered instrumented robot gripper
2. Tendon actuated multifingered hand
3. Direct link multifingered hand.

4.10.1.1. Two-Fingered Instrumented Robot Gripper

A two fingered instrumented gripper shown inFig. 4.26 has been developed by the authors and attached to a SCARA robot. The sensors employed are as follows:

Figure 4.26 Two-fingered instrumented gripper



a. Proximity sensor is employed to find out the vertical nearness of the gripper with respect to the object as this is mounted on the distal end of SCARA.

b. Infrared sensor has been used to detect whether the object is within the two jaws of the gripper or not.

c. Strain gauges are utilized to measure the grasping force.

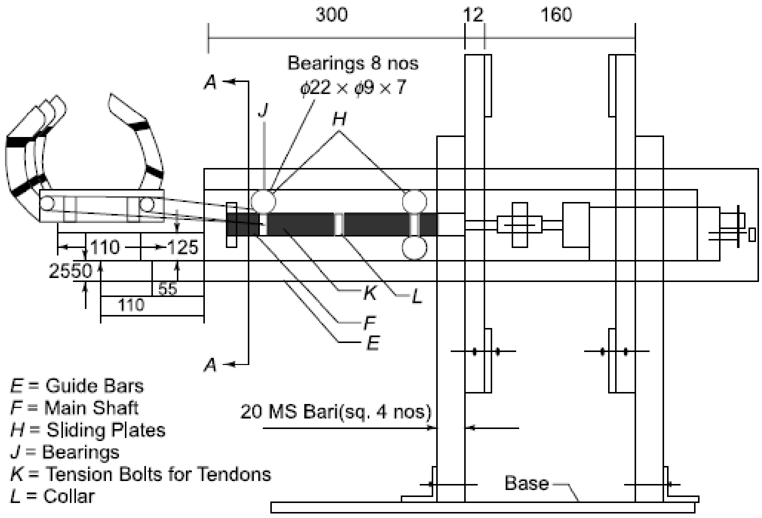
d. LVDT is placed to preshape the fingers according to the size of the object i.e. to maintain the gap in between the two jaws.

4.10.1.2. Tendon Actuated Multi-Fingered Hand

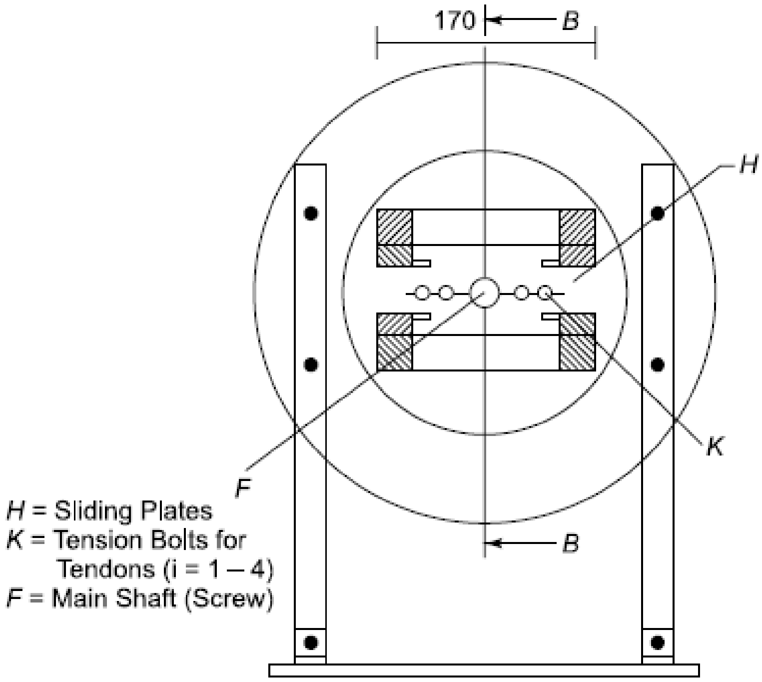
This design is a four-fingered robotic hand, shown in Fig. 4.27 which has been designed with the following major mechanical components:

- Elbow with roll motion
- Forearm
- Wrist with palm
- Three fingers namely index finger, middle finger and ring finger with three joints on each finger, the thumb with two effective joints and a base.

Figure 4.27 *Multi-fingered tendon actuated dexterous robot gripper with mechanical elements*



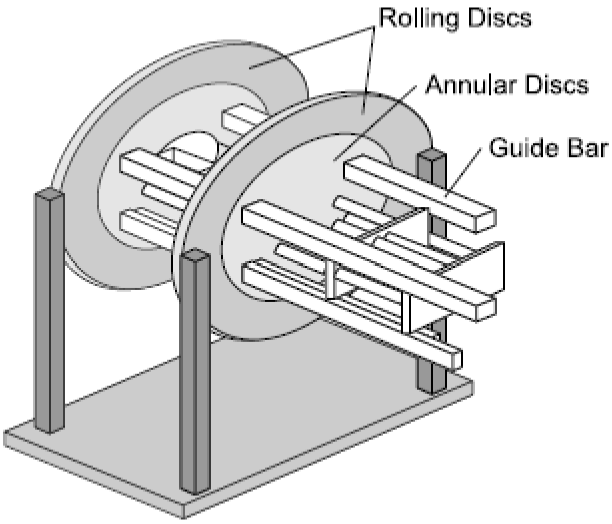
(a) Longitudinal view of the robotic gripper with palm upwards



(b) Sectional view Indicating Supporting Column, Sliding Plates and Main Shaft along AA

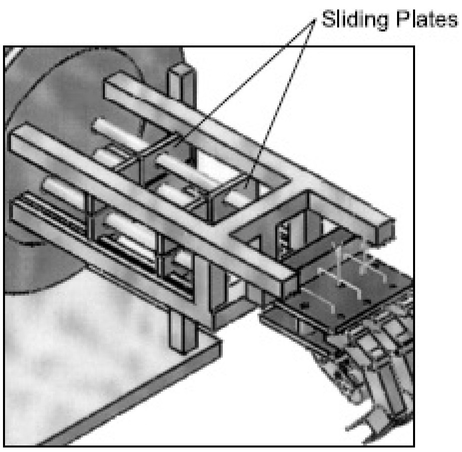
Elbow The design scheme of elbow shown in Fig. 4.28 consists of two annular discs, duly supported by four columns, rigidly fixed on base, for accomplishing roll motion. Two rolling discs have been provided on two annular discs. The rolling discs have a bearing at the center to accommodate the main shaft. The rolling discs have got four rectangular through holes to hold the four guide bars of the forearm. With the elbow roll motion, the palm can be configured with the palm up, palm down, left or right, sideward and can be rolled up to 360°.

Figure 4.28 *Elbow mechanism*



Forearm The forearm shown in Fig. 4.29 consists of four square bars which have a rectangular slot to accommodate bearings for smoother movement of the two sliding plates. The bearings are mounted on the two slides. The main shaft acting as a lead screw mounted on two bearings passes through the sliding plates has both right hand and left hand threads on the two sides of the collar in the mid position. The sliding plates either come closer or go apart with the rotation of the lead screw.

Figure 4.29 *Forearm of the gripper*



Fingers, Palm and Wrist The wrist holds the palm with the fingers rigidly with the forearm. The palm consists of two plates separated by three cylindrical collars at the wrist end and three supports of metacarpophalangeal joints at the finger ends. The muscle tendons for finger actuation pass through the intermediate gap of the square plates. The palm designs have been made one with (a) axially located fingers and the other with (b) radially located fingers shown in Figs 4.30 and 4.31, respectively. In the axially located configuration, the thumb has two degrees of freedom and in the radially located fingers, the thumb has three degrees of freedom. Each of the index, middle and ring fingers has three links namely distal link, proximal link and metacarpophalangeal link with their corres-ponding joints.

Figure 4.30 Axially located fingers

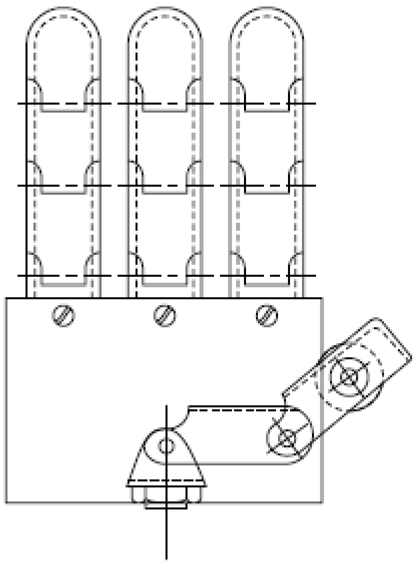
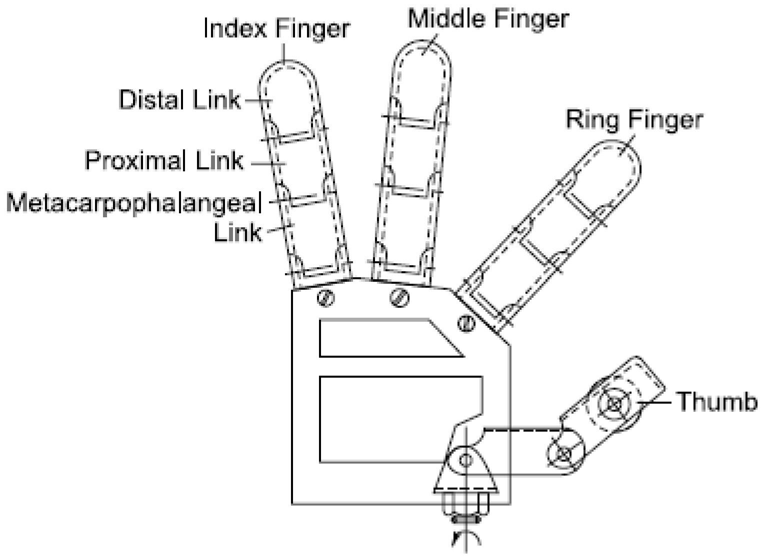
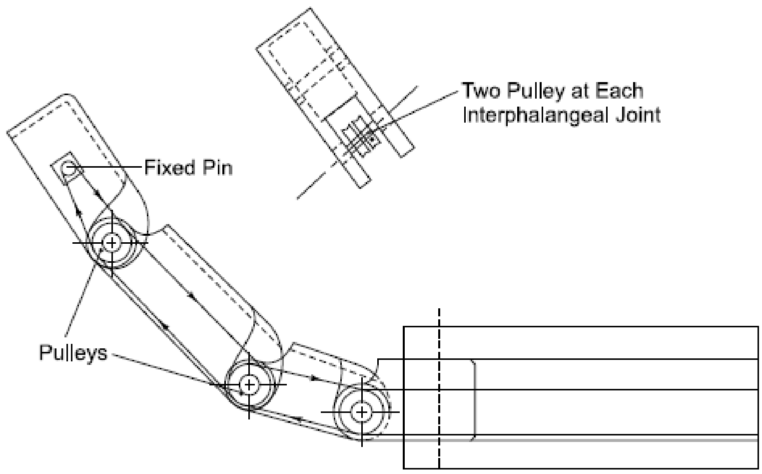


Figure 4.31 Radially located fingers



Finger Actuation and Tendon Winding Each distal link has one fixed pin as shown in Fig. 4.32 from which two muscle tendons namely pulling tendon and releasing tendon originate. At each interphalangeal joint two pulleys are present to guide the pulling and releasing tendons separately.

Figure 4.32 *Tendon actuation mechanism*



There is a correlation between motor torque and grasping force. The torque can be estimated from Fig. 4.33.

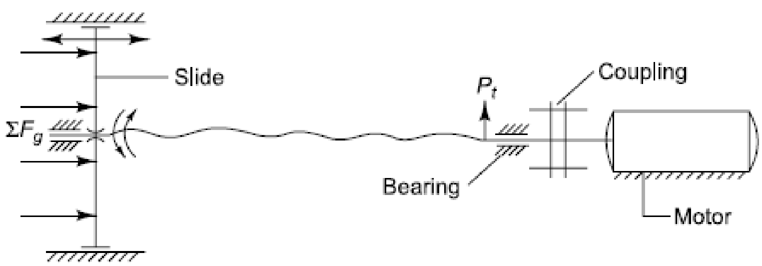
$$P_t = (\Sigma F_t) \tan (\alpha + \psi),$$

where

α = helix angle of screwed main shaft and ψ = angle of friction.

P_t = the tangential force acting on the shaft.

Figure 4.33 *Motor driven screw*



The torque of the motor, M_t, can be expressed as

$$M_t = P_t \times d_s / 2$$

where d_s = diameter of the main shaft.

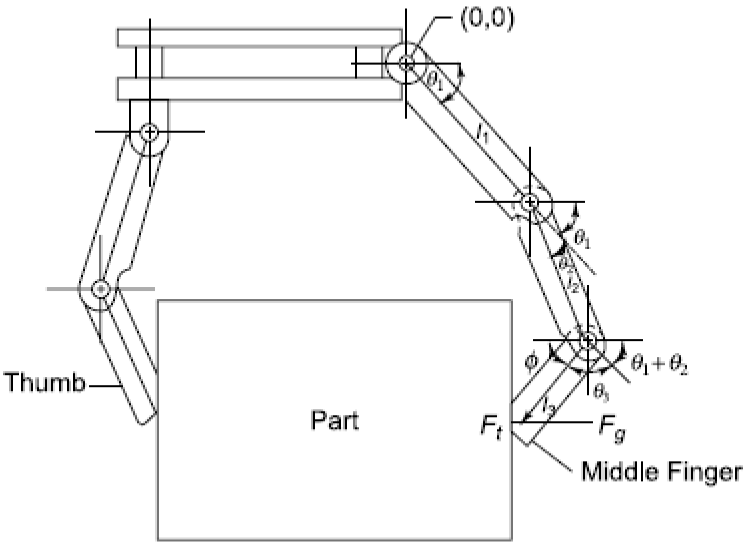
The tendon force propagates from the metacarpophalangeal joint to the distal link through the kinematic linkages when the object is in contact with the fingertip. A component of the tendon force (F_t) acts normal to the surface of the object being grasped. So the grasping force is a function of tendon force and the angle, ϕ between tendon force and the grasping force (F_g).

From Fig. 4.34,

$$F_g = f\,(F_t, \phi)$$

where F_g = grasping force normal to the surface, F_t = tendon force, ϕ = angle between grasping force and tendon force.

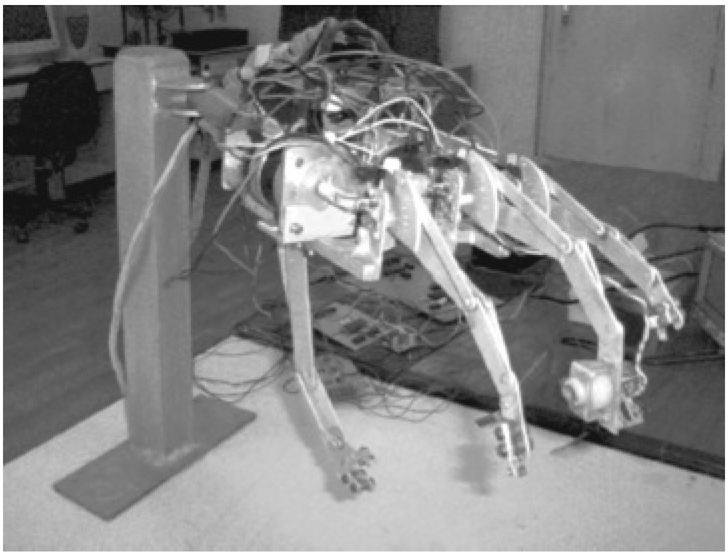
Figure 4.34 *Grasping force to hold the part*



4.10.1.3. Direct Linked Hand

A four-fingered direct linked robotic hand has been developed consisting of index finger, middle finger, ring finger and a thumb. All the fingers except the thumb consists of three joints as distal, proximal and metacarpophangial joints while the thumb has only two joints namely interphangeal and carpometacarpal joints. The photograph of a direct lined hand is shown in Fig. 4.35.

Figure 4.35 *Direct linked hand*



In the mechanism of direct linked system, as shown in Fig. 4.36, the crank is given the prime motion, which presses the push link–1 to turn the middle link about the proximal joint. With the rotation of the middle link, distal link turns simultaneously. The link movements stop when the lock pin comes in contact with the proximal link. At this position, the whole finger moves as an integral part. The crank is given motion through motor coupled with worm–worm wheel mechanism.

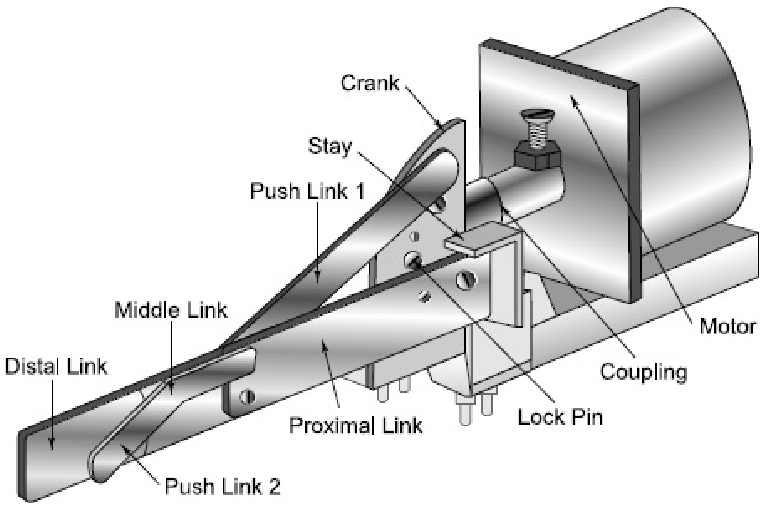


Figure 4.36 The direct-linked robotic finger

It ultimately presses the push link-1 to turn the middle link about proximal joint. As the middle link starts rotating, it turns the distal link simultaneously, since the distal link, middle link and push link-2 form a crossed four bar linkage mechanism. The crank is coupled to a small axle on which a worm wheel is mounted and the worm is directly coupled to a motor shown in Fig. 4.37.

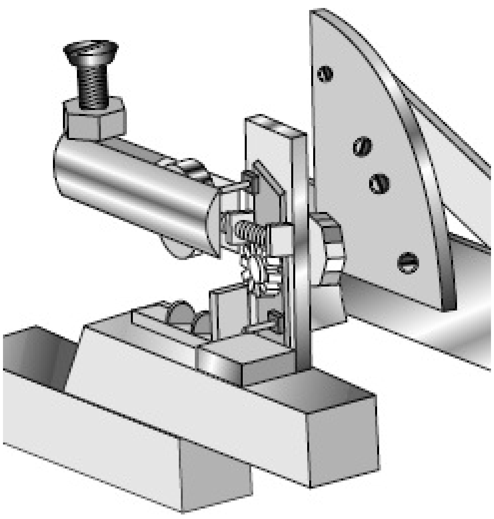


Figure 4.37 Direct-linked finger with worm–worm wheel attachment

4.10.2. Designing Multi-Degrees of Freedom Robot Fingers Based on the Mechanism of Human Hand

The human joint structures may be the starting point for the development of a multiple degrees of freedom robotic hand. The human hand possesses different motion characteristics like adduction and abduction shown in Fig. 4.38(a), flexion and extension shown in Fig. 4.38(b) and circumduction shown in Fig. 4.38(c). Figure 4.39 indicates the lateral view of the three phalanxes of human finger joints, namely distal phalanx, middle phalanx and proximal phalanx from the finger tip to the direction towards palm except the thumb. A typical range of the phalanges motions in the human hand is shown in Table 4.1.

Table 4.1 Typical Range of Phalanx Motions

Joints	*Articulation type*	*Angle (in degree) average value*
Thumb basal joint	Palmar Adduction/Abduction	45°
	Radial Adduction/Abduction	60°
Thumb DIP joints	Extension/Flexion	80°
Thumb MCP joints	Extension/Flexion	80°
Finger DIP joints	Extension/Flexion	60°– 65°
Finger PIP joints	Extension/Flexion	100°
Finger MCP joints	Extension/Flexion	−15° to 75°

Figure 4.38 The motions

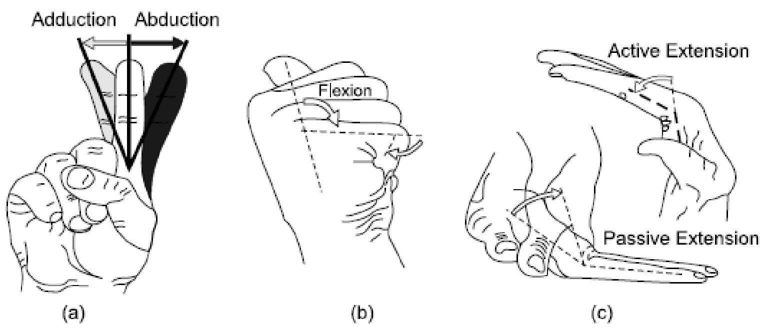
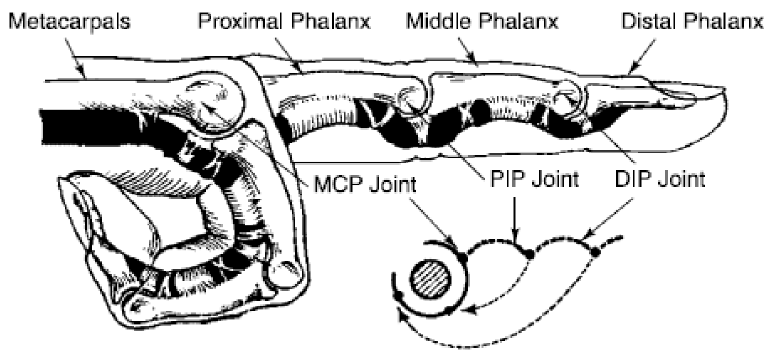


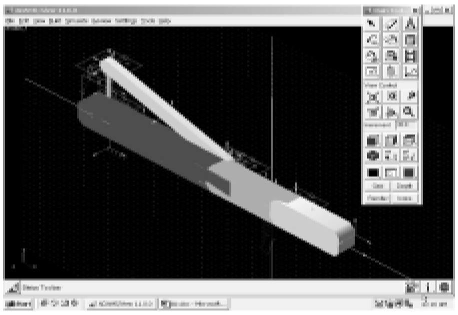
Figure 4.39 The joints



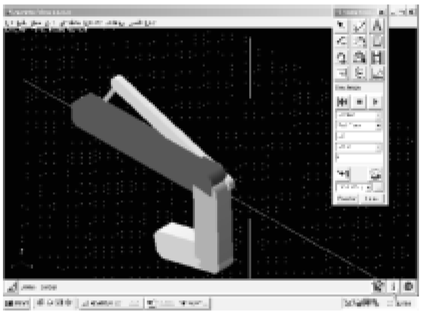
The finger design of a direct linked robotic hand has been already illustrated inFig. 4.36.

The range synthesis of the direct linked robotic hand has been carried out using ADAMS (Advanced Dynamic Analysis of Mechanical Systems)—a simulation software—and the results conform to the angles between phalanges of human hand shown in Table 4.1. The initial posture of the finger in straight position is shown in Fig. 4.40(a) and the link orientations after simulation for the fingers are illustrated in Fig. 4.40(b).

Figure 4.40 (a) Initial posture of the finger (b) Link orientations after simulation for index, middle and ring fingers



(a)



(b)

The angular displacements are illustrated in Fig. 4.41. DIP and PIP angles were initially 180°, but at the end, distal angle is 117.27° and proximal angle is 82.58°. So, the difference in distal angle is 63.67° and proximal angle shows 97.41° which conform to the angles in Table 4.1. The crank is rotated through (90 – 56.321°) or 33.679° to accomplish the whole movement of the finger. With the rotation of crank angle of 33.679°, the distal angle is 63.67° (60–65°) and proximal angle is 97.41° (100°). The simulated plot for the postures of the thumb has been depicted in Fig. 4.42. It is evident that the DIP and carpo-metacarpal joints have been turned by about 80° for the corresponding crank movement of 29.354°.

Figure 4.41 The angular displacements of the different phalanx for ring, middle and index finger

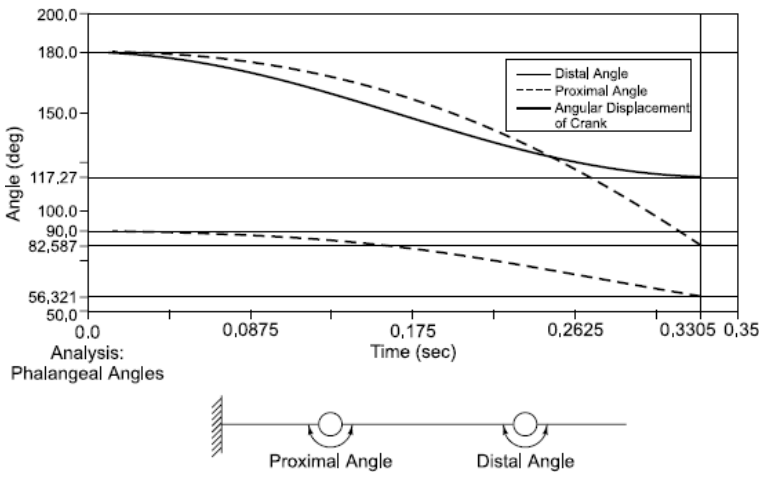
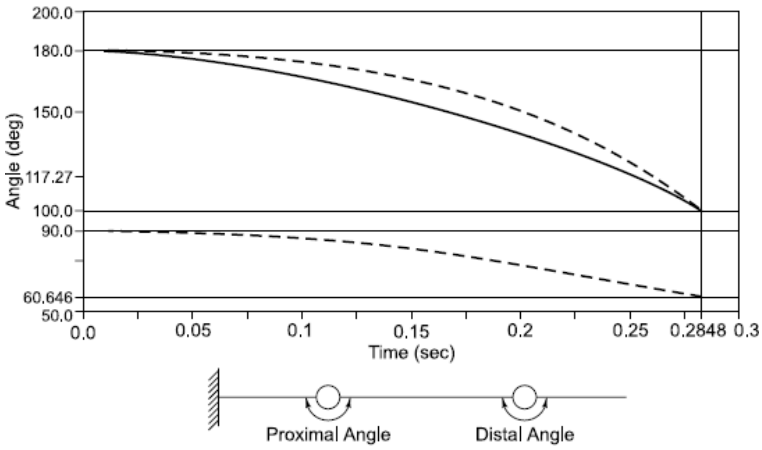


Figure 4.42 *The angular displacements of the different phalanx of thumb*



4.10.3. Force Analysis of the Phalanges

The finger is an assemblage of six links, out of which four are simply binary links and the other two are ternary links. Figure 4.43 indicates that four binary links are crank, push link-1, push link-2 and distal link. The ternary links are middle link and proximal link. The crank is the prime mover. With an application of load P_T at a particular crank angle θ_2, the distal link of the middle finger (say), imposes a gripping force of *F*'. The gripping force *F*' can be expressed by

$$F' = \frac{l_4 P_T}{r' r l_5} = c P_T$$

where *C* is a constant depending on link lengths and angular displacements and while,

$$r = \frac{l_1 l_4}{s^2}\left[\frac{l_2^2 + s^2 - l_1^2}{2 l_1 l_2} + \frac{\sin(\theta_2 l_3^2 + s^2 - l_4^2)}{\sqrt{\{s^2 - (l_3 - l_4)^2\}\{(l_3 + l_4)^2 - s^2\}}}\right]$$

$$s^2 = l_1^2 + l_2^2 - 2 l_1 l_2 \cos\theta_2$$

$$r' = \frac{l_7 l_8}{s*^2}\left[\frac{l_s^2 + s*^2 - l_5^2}{2 l_8 l_5} + \frac{\sin(\theta_4 - \theta_0)(s*^2 + l_6^2 - l_7^2)}{\sqrt{\{(l_6 + l_7)^2 - s*^2\} - \{s*^2 - (l_6 + l_7)^2\}}}\right]$$

when

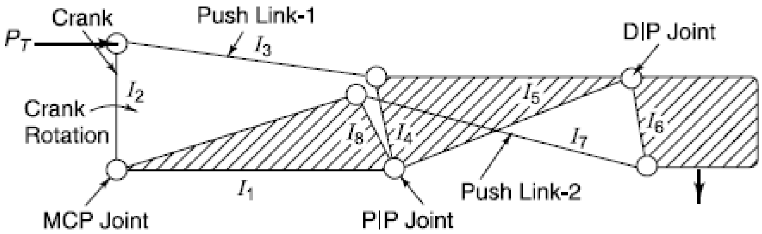
$$s*^2 = l_5^2 + l_8^2 - 2 l_5 l_8 \cos(\theta_8 + \theta_0 - \theta_4) \text{ and}$$

θ_i = Angles during flexion

s = Instantaneous length between crank pin joint and PIP point

s^* = Instantaneous length in between DIP joint and junction of push link-2 and proximal link.

Figure 4.43 The kinematic linkages equivalence for the finger



4.10.4. Graphical Simulation and FEA Modelling of the Robot Fingers

Graphical simulation using Mechanical Desktop has been attempted for solid modelling of the hand. All the fingers attached to the palm have been designed using the graphics tool. The total analysis has been carried out in Visual Nastran 4D, an FEA (Finite Element Analysis) model for both dynamic motion and stress analysis in assembled condition. The graphics files are exported to Visual Nastran 4D and the material and the torque constraints are defined. The object shapes namely—Cylindrical, Cuboidal and Spherical, materials, load and size of the objects with the same weight are also given.

From an initial load of 5 kg, the load was reduced to 0.65 kg. when torque is enough to grasp the object securely with the robot hand.

Figures 4.44 and 4.45 indicate the examples of simulation results of the cylindrical and cuboidal parts respectively. In a similar way, the simulation results of the spherical jobs may be obtained and are shown in Fig. 4.46.

Figure 4.44 Simulations for grasping of cylindrical jobs

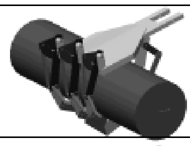
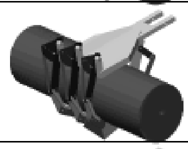
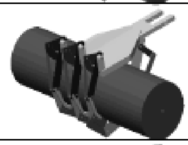
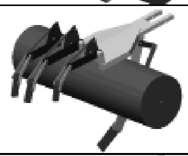
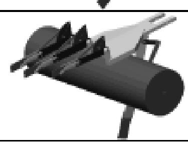
Step No.	*Simulated Figure*	*Remarks*
1.		Hand is in home position.
2.		The fingers shape to grasp the object.
3.		The fingers wraps the object.
4.		The object starts to get reoriented.
5.		Reorientation stops and stable grasping is achieved.

Figure 4.45 Simulations for grasping of cuboidal jobs

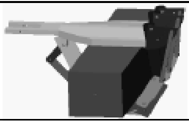
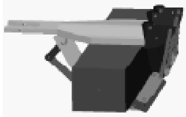
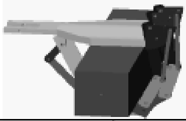
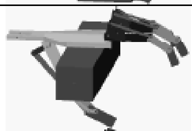
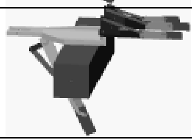
Step No.	*Simulated Figure*	*Remarks*
1.		Hand is in home position.
2.		The fingers shape to grasp the object.
3.		The fingers wrap the object.
4.		The object starts to get reoriented.
5.		Reorientation stops and stable grasping is achieved.

Figure 4.46 Hand with uniform finger motions to grasp spherical object

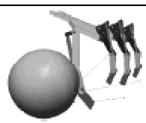
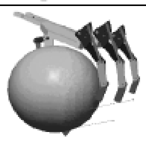
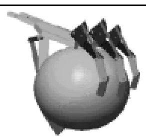
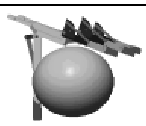
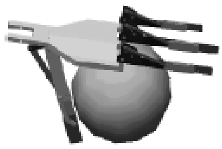
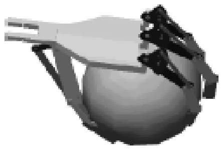
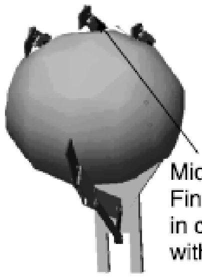
Step No.	*Simulated Figure*	*Remarks*
1.		Hand is in home position.
2.		The fingers shape to grasp and wrap the object. Fingers are being actuated with uniform velocity.
3.		The object slips sideward and comes out of the grip as the ring finger is coming much later to restrict its sidewise motion.
4.		The object comes totally outward due to unbalance moment.

Figure 4.46 shows the effect of sequence of finger motions and redundancy. A Sphere of 200 mm diameter and weight of 0.65 kg is illustrated with different finger sequences. It has been found that middle finger is the redundant finger for grasping spherical object.

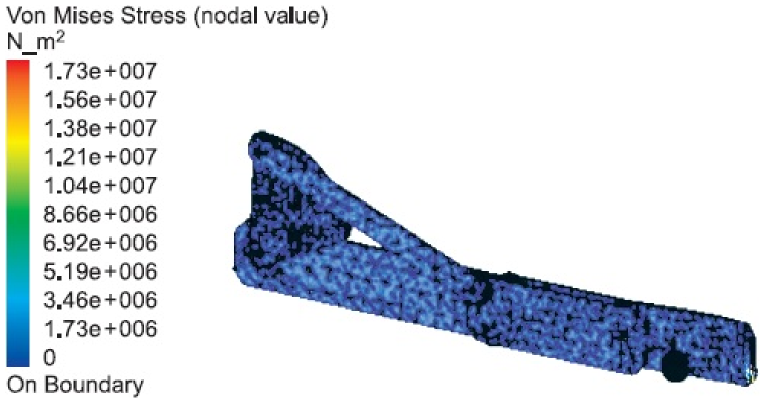
Figure 4.47 shows stable grasping with non-uniform finger motions.

Figure 4.47 Hand with non-uniform finger motions to grasp a spherical object

Step No.	*Simulated Figure*	*Remarks*
1.		Hand is in home position.
2.		The fingers shape to grasp and wrap the object. The velocity for ring and index finger is higher than the other two fingers.
3.		The object is firmly held with the fingers and the thumb but middle finger is not in contact with the job.

Using CATIA Finite Element Analysis (FEA) modelling, the thickness of the finger was optimized. In a typical finger, total elements were 31099 and node numbers were 56715. The analysis was done in straightened condition. Material was aluminium and 500 g load was given at the distal fingertip. The stress values were calculated and shown in Fig. 4.48.

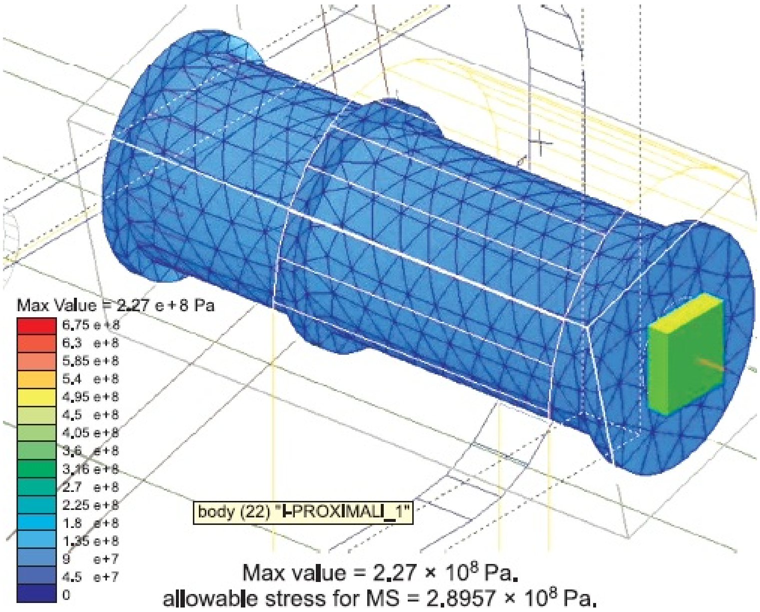
Figure 4.48 The finite element analysis of the finger for static condition



Design modifications have been made using FEA for the design of axles in different joints. For example, the axles present in the metacarpophalangial joints are the most crucial from the stress point of view. Material of the axles have been changed from aluminium to steel C–20 with 6 mm diameter. With steel axles, the performance has been found to be improved.

Figure 4.49 shows the developed stress on the axles. Thus FEA and graphical simulation are important tools for the mechanical design of the robot grippers.

Figure 4.49 FEA for axle for metacarpohalangeal joint



4.11. ACTIVE AND PASSIVE GRIPPERS

Most of the industrial robot end-effectors are passive in the sense that they do not have any 'feeling'. They work on open loop system. In a variety of cases, a robot needs feedback sensors. The sensors may be on the wrist or on fingers. Then the robot end-effector becomes active. There are experimental universal grippers with many degrees of freedom like the human hand. They are called adaptable grippers. Okada described a novel design of versatile gripper with three fingers namely a thumb, an index finger and a middle finger. The tubular phalanges can be bent ±45° in each joint. The hand has active wire-line drive to actuate the links. A five-finger hand has also been developed for prosthetics. However there are two-finger servoed gripper with sensors at different positions. To conform to the periphery of the objects of any shape, soft grippers with grip and release wire have been developed by different researchers, including *S*. Hirose et al. and Deb et al. Depending on the situation, industrial tasks can be accomplished using either active wrist with passive fingers or passive wrist with active fingers and in some cases, active wrist with active fingers.

4.12. EXERCISES

4.1 Name five different types of robot end-effecfors. Compare and contrast the end-effectors from the view-point of their functions.

4.2 With the aid of a sketch describe briefly the mounting of a welding torch gun on a robot wrist.

4.3

a. Calculate the vacuum cup area for grasping a plate weighing 200 pounds if the number of vacuum cups on the end-effector is 4. Pressure differential is 10 psi.

   [Use no. of cups × cup area × ($p_{\text{atmos press}} - p_{\text{inside press}}$) = weight of plate]

b. If frictional coefficient μ is 0.4 and safety factor for the above problem is 2, what is area of the vacuum cup?

$$A = \frac{W}{\mu(\delta p)FS}$$

Given:

$$\begin{aligned} \mu &= 0.4 \\ FS &= 2 \\ p &= 10 \text{ psi} \\ W &= 200 \text{ lbs} \end{aligned}$$

4.4 Illustrate a robot gripper with

a. self-aligning fingers

b. form dependent finger

4.5 Illustrate a robot gripper with

a. cam operated

b. gear operated

c. lever (links) operated fingers.

4.6 Distinguish between two-point and three-point centering of robot gripper.

4.7 What are the types of actuators used for robot end-effectors? State the advantage of each actuator.

4.8 Distinguish between servoed and non-servoed grippers. What are the actuators used for such grippers.

4.9 What is a compliant gripper? Why are compliant fingers used?

4.10 What is remote centre compliance device? What are the lateral error and the angular error involved in inserting a peg in a hole? How does RCC overcome these errors?

4.11 What are the design considerations in the robot end-of-the-arm tooling?

4.12 How is a robot end-effector specified?

4.13 Sketch some linkage mechanisms for mechanical grippers.

4.14 Using a diagram, briefly explain the parallel action robot gripper.

4.15 A part weighing 5 kgf is to be held by a robot end-effector having two fingers. The coefficient of friction between the fingers and the part is 0.25. Assume g factor to be 3.0. Assuming that the weight of the part is applied in a direction parallel to the contacting finger surfaces, estimate the gripping force.

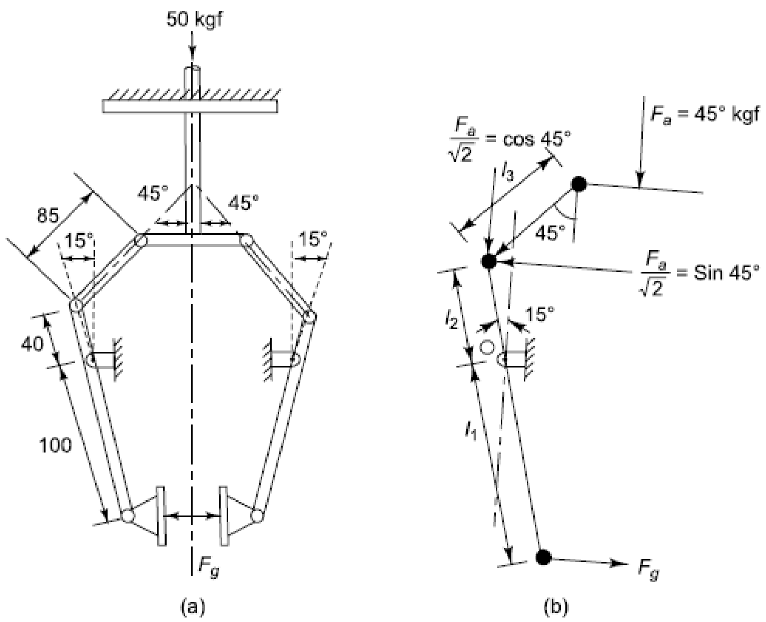
4.16 The gripper as shown in Fig. 4.50 is required to hold the workpiece. An actuating force of 50 kgf is acting vertically downwards resulting in a gripping force F_g. Compute the maximum gripping force that can be applied.

Hint: $\Sigma M = 0$ about the flucrum 0 [Fig. 4.50(b)].

$$F_g \times l_1 \cos 15° = \left(\frac{F_a}{\sqrt{2}} \sin 45°\right) \cdot l_2 \cos 15° + \left(\frac{F_a}{\sqrt{2}} \cos 45°\right) \cdot l_2 \sin 15°$$

from which F_g can be found.

Figure 4.50 Figure of exercise problem 4.16



4.17 A vacuum gripper is to lift a weight of 10 kgf, with the aid of a single suction cup having a diameter of 150 mm. Determine the negative pressure required to lift the weight.

4.18 A vacuum pump to be used is to maintain a pressure differential of 3 N/cm^2 (i.e. $p_{atm} - p_{res}$) compared to atmospheric pressure. The gripper is used to lift 400 mm × 900 mm plate having a net weight of 300 N. Assuming two suction cups engaged for lifting the weight, determine the diameter of the suction cups. Assume a factor of safety of 1.4.

4.19 A part is to be gripped by the link mechanisms as shown in Fig. 4.51. Estimate the actuating force P_a in terms of dimensions a, b, c if the force at contact between jaw and the part is N. Assume a coefficient of friction, μ. Neglect the angle of friction for the pins in the bearing.

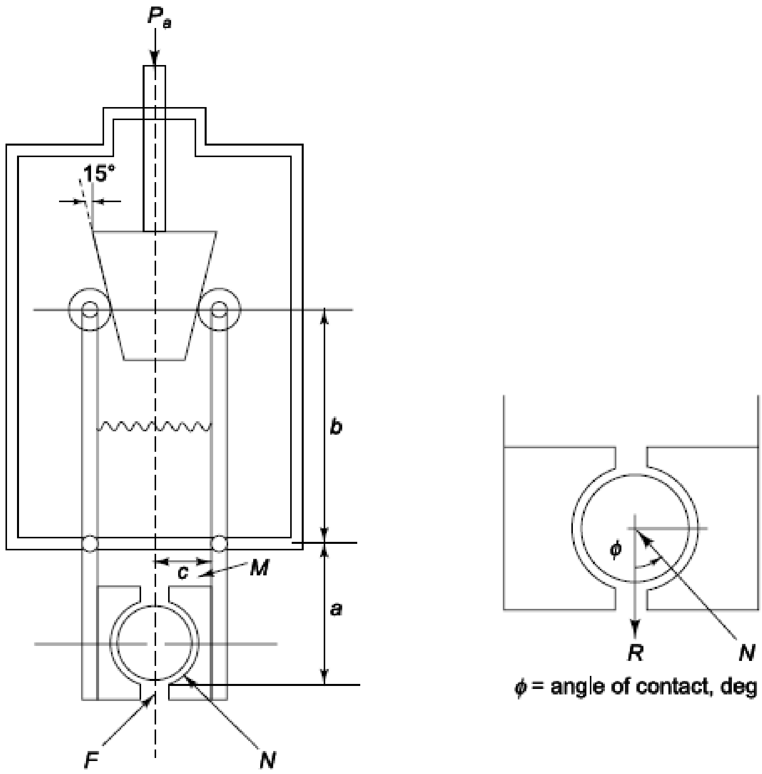


Figure 4.51 Figure of exercise problem 4.19

4.20 What are the advantages of using electromagnetic and vacuum systems in the robot gripper drive?

4.21 Classify the robot end-effector from the view point of control.

4.22 Discuss suitable design of robot end-effectors to grip objects like

a. shafts
b. rings
c. flanges
d. box type objects
e. flat pieces
f. contoured objects

4.23 With the aid of sketches describe some commonly used mechanical grippers.

4.24 Describe a robot gripper to take measurements of outer and inner dimensions of objects with the aid of pneumatic gauging.

4.25

a. What are the advantages of a multifingered gripper over two finger grippers?
b. What is meant by an instrumented robot hand? What are the sensors to be fitted to the robot gripper?

4.26 With the aid of a sketch describe (a) a tendon actuated multifingered robot gripper and (b) a direct linked multifingered robot gripper.

4.27

a. Distinguish between power grip and dexterous grip.

b. What are the main issues to be considered for designing multiple degrees of freedom robot hand?

4.28 What is FEA? How is it useful for designing the fingers of a robot hand?

4.29 How is the graphical simulation useful for the analysis of the finger actuation.

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