*Chapter 3*

# End effectors: hands, grippers, pickups and tools

End effectors are at the business end of the robot. These are the moving components which have to grasp, lift and manipulate workpieces without causing any damage, and without letting go. Compared with human hands those of the robot are but clumsy travesties. They have fewer articulations and they are without any sense of feeling or touch. But, they can be designed to withstand high temperatures so that they are able to work with parts that are red hot. They are better at dealing with objects with sharp edges, or covered with corrosive substances, or which would simply be too heavy for human hands to grasp.

Being less adaptable than human hands, robot hands have to be chosen or designed specially for a particular industrial application. Whereas the robots themselves have earned the reputation of being general purpose automation, the hands are not quite so flexible and may have to be included along with the special tooling requirements of the job. In practice, this is not likely to prove a monkey wrench in the economic works. One type of hand is usually going to be suitable for a wide range of different jobs at a particular work station. Only when the robot has to be redeployed elsewhere to work on an entirely different process is it likely that the hand tooling has to be changed. And, compared with overall plant and machinery costs, hands come relatively cheap.

## Methods of grasping

There are many ways of grasping or otherwise handling a job, depending to a large extent on the nature of the material being processed. Options include:

- Mechanical grippers.
- Hooking on to a part.
- Lifting and transferring a part on a thin platform or spatula.
- Scooping or ladling.
- Electromagnets.
- Vacuum cups.
- Sticky fingers, using adhesives.
- Quick disconnect bayonet sockets.

Some examples of appropriate methods are:

- Forgings – normally handled by massive steel hands.
- Thin metal sheets – vacuum cups and magnets are preferable in this case.
- Powders, granular solids, liquids and molten metals – ladles or scoops.
- Fabrics and similar flimsy material – vacuum cups, adhesives, and electrostatic devices all offer possible solutions. Usually much ingenuity is necessary.
- Spot welding – weld gun permanently bolted to the robot wrist or exchangeable by means of bayonet socket.

## Mechanical grippers

The following are the main factors in determining how grippers should grasp, and how hard.

1. The first and obvious rule is that the surface which the industrial robot's hand is to grasp must be reachable. As an example, it should not be hidden in a chuck.
2. Consider the tolerance of the surface we grasp and its influence on the accuracy in placing a part. If the machined portion of a cast part is to be inserted into a chuck – and the robot must grasp the cast surface – the opening in the chuck must be larger than the eccentricity between the cast and the machined surfaces.
3. The hand and fingers must be able to accommodate the change in dimension of a part that may occur between the part loading and the part unloading operations.
4. Consider how delicate surfaces are to be grasped and whether they may be distorted or scratched.
5. Select the larger if there is a choice of grasping a part on either of two different dimensions. Normally, this will assure better control in positioning the part.
6. Fingers should have either resilient pads or self-aligning jaws that will conform to the part to be picked up.

The reason for self-aligning jaws is to ensure that each jaw contacts the parts on two spots. If each jaw contacted the part on only one spot, the part could pivot between the jaws.

How hard the robot must grasp the part depends on the weight of the part, the friction between the part and the fingers (vacuum cups or magnet) how fast the robot is to move and the relation between the direction of movement to the fingers' position on the part. The worst case is when the acceleration forces are parallel to the contact surface of the fingers. Then friction alone has to hold the part.

A robot at normal full speed may, during acceleration and deceleration, very well exert forces on a part of about 2g (twice the earth's gravity). The following relationships are of interest:

1 A part transferred by a robot in the horizontal plane will exert a force on the hand tooling of twice the weight of the part.
2 If the part is lifted, it will exert a force three times its weight, 1g due to the earth's gravity and 2g due to acceleration upwards made by the robot.

The amount of friction which exists between the part and the fingers of the robot must also enter the picture. Consider the following example:

A weight of 25 pounds is to be lifted by a robot. The gravitational forces are parallel to the contact surfaces of the fingers and tend to pull the weight out of the hand. If the friction coefficient is 0.15, how hard must the robot grasp the part? Include a reasonable safety factor in the solution. The equation for this situation is:

clamping force x friction coefficient = tangential force
= weight of the part x g-loading.

This reduces to:

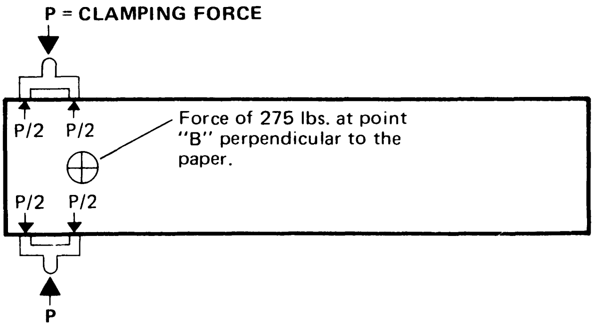
clamping force x 0.15 = 25 x 3
i.e. clamping force = 500 lbs
With a safety factor of two, the clamping force should therefore be 1000 pounds.

If the center of gravity of the part is outside the line between the two jaws, a moment due to acceleration forces will tend to pivot the part. To prevent pivoting the product of the clamping force, the spread between contact points and friction must be greater than the moment. An example of the method of calculating grasping force is given in Figure 3.1.

A part weighs 25 lbs and has a center of gravity 15" off the point where it is grasped. The friction coefficient is 0.15 and the spread between the contact point on each jaw pad is 3". How hard must the robot grasp to have a safety factor of 2 on its hold of the part?

It is necessary to design for the highest force which will occur at the point where slippage between fingers and the part will first arise, if the clamping force is not high enough.

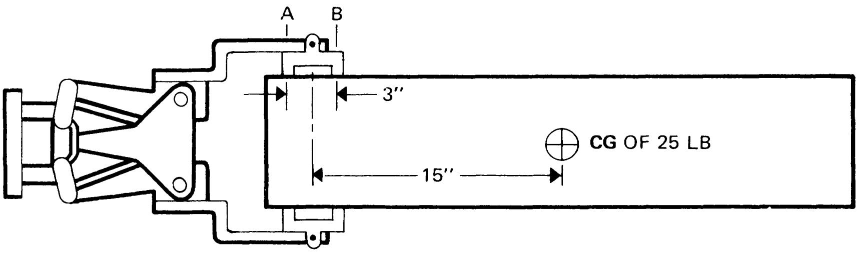
**Figure 3.1** *Example showing calculation of grasping force*



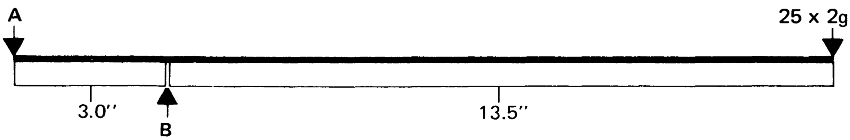

clamping force x friction coefficient ($\mu$)
$\geqslant$ force at point "B"
2 (P/2 x $\mu$) = B
2 (P/2 x 0.15) = 275
P = 1830 lbs
with a safety factor of 2, the required clamping force is 3660 lbs.

This is a very large clamping force for a 25 lb part, which indicates that the design is not efficient. The force can be reduced in two ways: first, try to grasp the part closer to CG or make the pads longer (6" instead of 3" will reduce the clamping force from 3660 to 1340 lbs).

The situation may be represented thus:




This simplifies into the following force diagram:

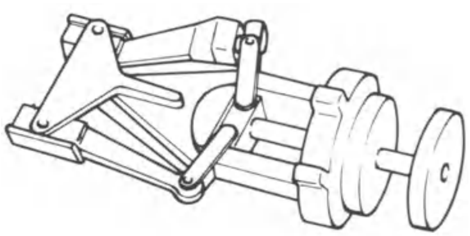



force at point "A" =
$$\frac{25 \times 2}{3} \times 13.5 = 225 \text{ lbs}$$

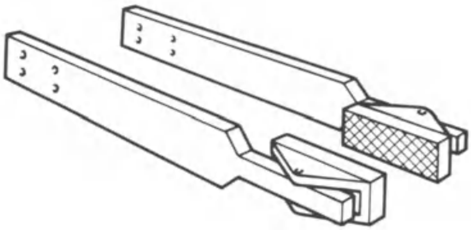
force at point "B" =
225 + (25 x 2) = 275 lbs

*Figure 3.1 (continued)*

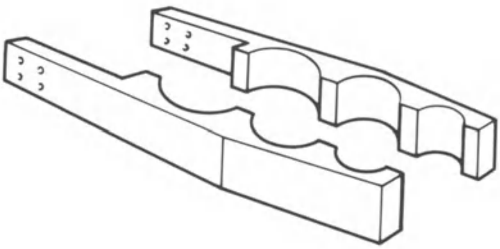
Some indication of the very wide variety of mechanical grippers which have been designed to meet different robot applications can be gained from Figure 3.2. The selection is by no means representative of all that is available or possible. As previously mentioned, grippers are the one area of robotization where specialized design of tooling is often necessary though it is seldom expensive.



*Standard hand*
This is an inexpensive and all-purpose hand that will accept a virtually infinite variety of custom fingers. Fingers are tailored to the parts to be manipulated or moved. The parts should be of moderate weight. Simple linkages provide both the finger action and the force multiplication needed to grip the object sufficiently tightly. At the completion of finger closure, the fingers exert their maximum clamping force on the part.

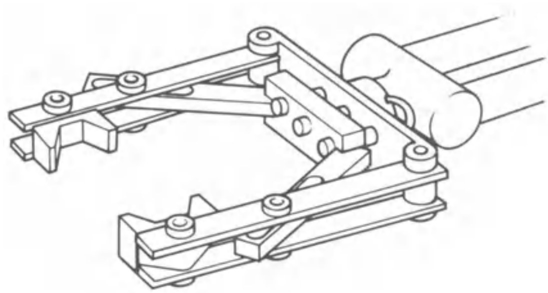


*Fingers self-aligning*
Self-aligning pads for fingers are valuable for assuring a secure grip on a flat-sided part. 'Cocking' of the part is highly unlikely when these pads are employed.

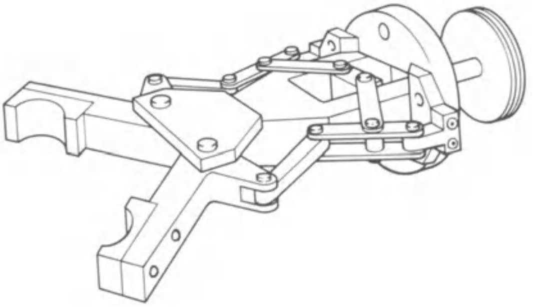


*Fingers for grasping different size parts*
A particular finger design need not be restricted to parts within a limited range of sizes. Perhaps the fingers can be equipped with extended pads having several cavities for parts of differing sizes and shapes, or for parts that change shape during processing. Then, the industrial robot is pre-programmed to position the hand so that the proper cavity will match the location of the part.

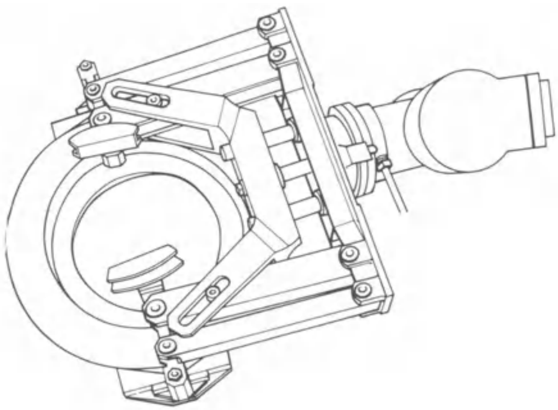
Figure 3.2 *Examples of mechanical grippers*



*Cam-operated hand*
Heavy weights or bulky objects are handled easily by the cam-operated hand. More expensive than the standard hand, the cam-operated hand is designed to hold the part so that its center of gravity (CG) is kept very close to the 'wrist' of the hand. The short distance between the CG and wrist minimizes the twisting tendency of a heavy or bulky object. To achieve this 'close coupling' of hand and part, there is a sacrifice: a specific cam-operated hand design will accommodate only a very narrow range of object sizes.

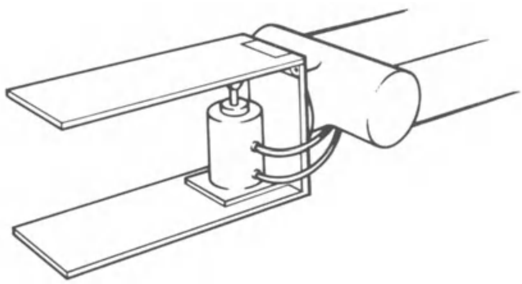


*Wide-opening hand*
When the part to be picked up is not always to be found in a constant orientation or at the same site, a wide-opening hand may be recommended. As it closes, this hand will sweep the inexactly located part into its grasp.
If the part to be grasped is always precisely positioned for pick-up, the wide-opening hand can shorten the time needed to reach for the part. The hand can travel the shortest path to the part and skip the extra step of making its final approach to the part from one specific direction. The hand develops low force when open and maximum force when closed. It is for parts of moderate weight.

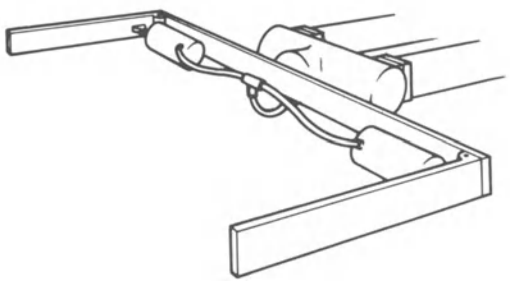


*Cam-operated hand with inside and outside jaws*
Assume that a part is re-oriented between the time when the part is placed in a machine and when it is removed. This special hand is one of those which will deal with this problem. When the part is oriented as shown, the hand can grasp it on the OD by employing the outer self-aligning pads. If the part is turned over, the inner pads will grasp the ID.
A similar principle applies when the grasped surface of a part is changed significantly between the time when it is placed in a machine and the time when it is removed. A special hand can be designed to deal with most changes in ID, OD, or other dimension.

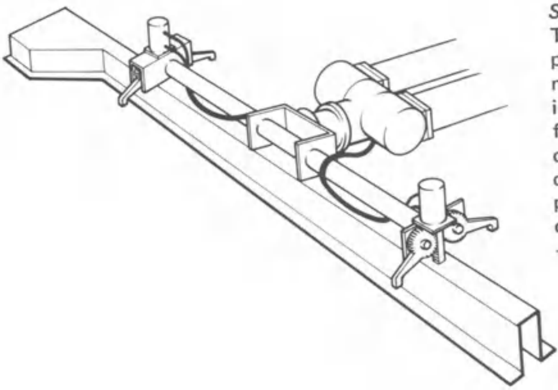
*Figure 3.2 (continued)*



***Special hand with one movable jaw***
A hand with single-acting jaw should be considered when there is any access underneath a part, as when it is on a rack. Where this hand can be applied, it will scoop up a part quite quickly. Simplicity of the design makes this one of the most economical hands.

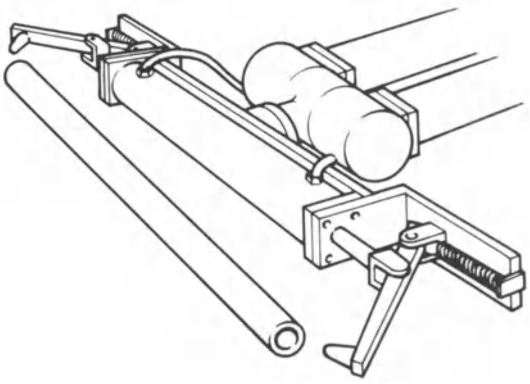


*Special hand for cartons*
The dual-jaw hand will open wide to grasp inexactly located objects of light weight. Lifting and placement of cardboard cartons is an application. Actuators and jaws can be re-mounted in any of several positions on the fixed back plate, making it practical for the same dual-jaw hand to move large cartons on one day and smaller cartons the next.

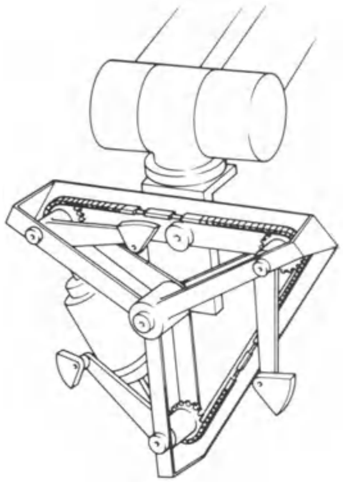


*Special hand with modular gripper*
This special hand, with pair of pneumatic actuators, is one of the many special hand designs for industrial robots. It would be suitable for parts of light weight. Lifting capacity is dependent upon friction developed by the fingers, but heavier parts could be handled if the fingers could secure a more positive purchase — as under a flange or lip.

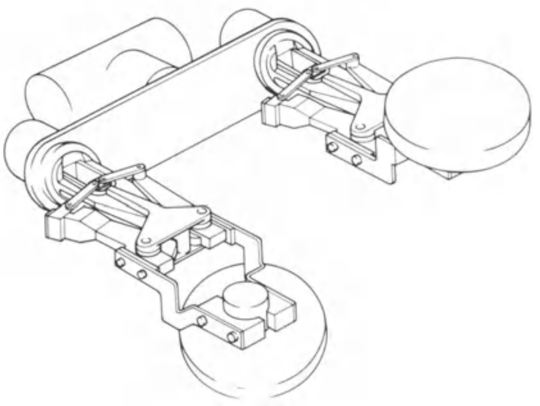
*Figure 3.2 (continued)*



*Special hand for glass tubes*
Secure grasping of relatively short tubes is the forte of this special hand for an industrial robot. Pick-up will be as effective even when tube length varies somewhat. The fingers of the hand close in two stages: First, they travel through an arc until they are vertical; Second, the actuator draws them together axially. Linear travel in this second stage of closure is selected to accommodate the range of tube lengths to be handled.



*Special hand chuck type*
It is practical to handle drums and similar large cylindrical parts with a relatively simple mechanism consisting of three fingers and a single actuator. The actuator drives all three fingers simultaneously by means of a chain and sprockets. The fingers expand against the inside diameter of the drum. One hand of this type will pick up drums of various diameters.



*Double hand*
Does a robot application call for the hand to remove a finished part from a machine and replace it with an unfinished part? A double hand with double actuators is a possible choice. It will pick a part out of the chuck of a machine, swivel, and place a new part back in the chuck, for instance. Thus, an industrial robot with this hand does not need to expend time to put one object down before it manipulates another: the hand seldom makes a trip while empty. Parts should not be of more than moderate weight when the double hand is used.

*Figure 3.2 (continued)*

## Vacuum systems

### *Vacuum cups*

Vacuum cups are normally made of an elastic material that conforms and forms a seal to the surface of the part to be handled. If the part is elastic, then of course the cup can be made of a hard material. The shape of the cups is mostly what the name implies – cup-shaped.

There are other configurations that differ in principle to the usual cup. Some cups, or vacuum pads, are made of cellular material through which the air is drawn. They have the advantage of working on a rough and porous surface; e.g., a common brick, because each cell constitutes its own little vacuum cup and if one fails to make a seal, it is paired up with neighboring cells and they together form a larger cup.

The holding force of a vacuum cup is the effective area multiplied by the different of pressure between the outside and inside of the cup.

The effective area of a cup is often not the geometric area, because the cup often deforms when vacuum is applied. If the bottom of the cup touches the object to be lifted, the effective area is reduced correspondingly.

To get the best utilization of a cup, the largest possible vacuum or pressure differential should be used. In most cases, which we will deal with later, it is better to use a larger cup and a lower vacuum to obtain a faster system.

The vacuum will not form until the cup has sealed on the part; therefore, to get speed out of a vacuum system, it is advantageous to mount the cups on spring-loaded stems and have the robot programmed so that the cup touches the part long before the arm reaches its final pick-up position. This will eliminate a large portion of the deceleration time from the cycle.

Springloading of the cups will also compensate for any variation in the height or level of the part. If there are any variations between the parts to be handled, like distorted sheet stock, it can often be compensated for by putting the cups on ball joints, as well as springloaded stems.

For sliding of the parts, the same rule applies as for fingers: the force multiplied by the friction coefficient between the cups and the material. If oily sheet stock is being picked up, the coefficient will not be simply the friction between rubber and metal; this is normally very low and, in most cases, the cup will not break through the oil film. In such cases viscous friction rather than Coulomb friction is present, which means that the sheets will always slide sideways to some extent when exposed to a force.

The life of vacuum cups is quite good, especially in relation to their price. Polyurethane cups seem to have a longer life than those made from natural or synthetic rubber. Vacuum cups are catalog items and there is a selection to choose from in both configurations and sizes.

The number of cups to be used in a design depends on such factors as: weight of the load, size of cups available, location of the center of gravity and the support needed to handle large flimsy parts.

*Vacuum pump* versus *venturi*

To create a vacuum a choice exists between two devices, the vacuum pump or the venturi. A vacuum pump is either a piston or vane-type pump driven by an electric motor. The venturi is a device where vacuum is created by having a secondary high energy stream of flow impinge on the primary flow actually converting pressure into vacuum.
The advantages of a pump are:

- Able to create a high vacuum
- Low cost of operation
- Relatively silent

Disadvantages:

- High initial cost
- Requires a more complex system: vacuum tank and blow-off valve

The advantages of a venturi:

- Low initial cost
- Does not normally need blow-off valve or vacuum tank
- High reliability

Disadvantages:

- Very noisy
- High cost of operation

The venturi system differs from the pump system in that it is not controlled by a valve in the vacuum line but rather by control of the high pressure air to the venturi.

By this control mode, the venturi is working only when vacuum is desired. Consequently, the size of the venturi has to be of full size and cannot utilize a low-duty cycle to charge and draw peak loads from an accumulator.

Since there is no valve in the vacuum line, the response time is not limited by it. Instead, the response is a function of the size of the venturi, and in the cases where the venturi is turned on after contact, by the time delay in the pressure line.

One simple way to make an estimate of the response is to establish the lowest pressure at which the vacuum cups can pick up the load and where this vacuum intersects the proper supply pressure line, read off the corresponding flow. Dividing the volume of the vacuum cups and the lines by this flow will yield the time it takes to evacuate the cups. This estimate is conservative since the venturi has a higher flow at lower vacuum.

*Special considerations*

While attention has been paid to the engagement of the parts to the cups, little has been mentioned about the disengagement which is of equal importance.

To release a part fast, a blow-off system is required. A typical arrangement of such a system is shown in the schematic of the pump-vacuum system.

In studies it has been found that the limiting factor of the speed of response is the size of the valves. Direct operated solenoid valves seldom have larger flow areas than 1/8th inch holes. For higher capacities of high speed valves, it is necessary to use a pilot operated valve. The ultimate system would then consist of a pilot-operated solenoid valve and plumbing sized accordingly.

Some typical vacuum pick-up systems are illustrated in Figure 3.3.

### Magnetic pickups

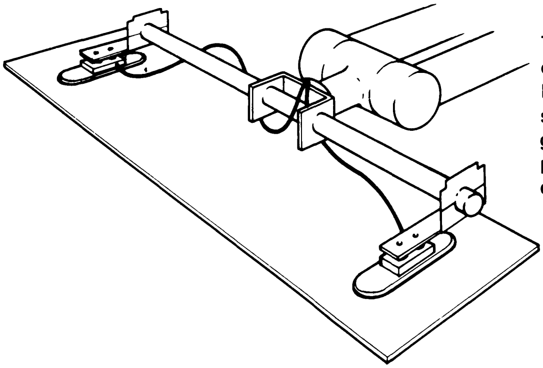
Parts handling for various processing operations can be accomplished in several ways but if the parts are of ferrous content, magnetic handling should be one of the methods to receive consideration.

Magnets can be scientifically designed and made in numerous shapes and sizes to perform various tasks. A ferrous object placed within the range of a magnet will itself become magnetized, and will then have its own North and South poles which will be attracted to the parent or larger magnet *in proportion to its mass.*

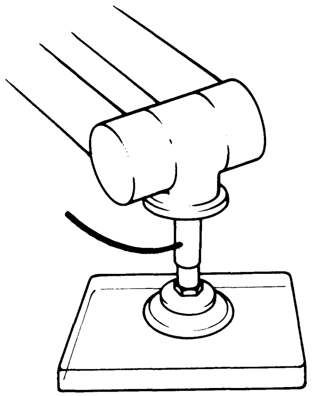
Magnets fall into two principal categories, namely permanent and electro. Either of these types can be adapted within reasonable limits to handle parts having various shapes and often it is possible to handle several different shapes with the same magnet.

Electro magnets are well suited for remote control as well as for moderately high speed pick up and release of parts. A source of D.C. power is required in connection with control equipment which should be selected for the specific application. To assist in releasing parts without hesitation, an item known as a 'drop controller' is incorporated in the circuit. Basically, it is a multi-function switch through which power is supplied to the magnet and as it interrupts the power supply, it reverses the polarity and supplies power at a reduced voltage for a short duration before completely disconnecting the magnet from the line. This reverse polarity tends to cancel any residual magnetism in the part to make sure that it will release instantaneously.

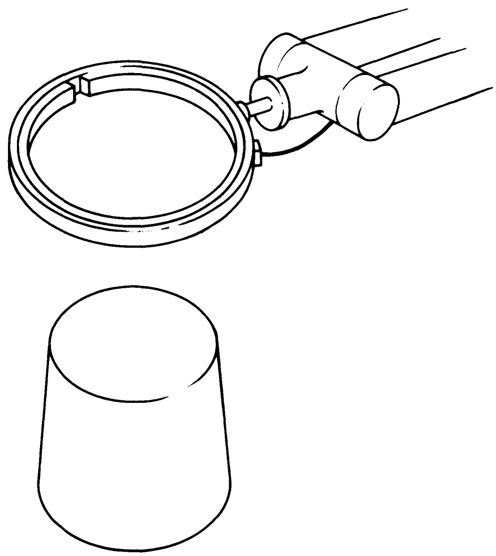
Permanent magnets do not require a power source for operation which makes them well adapted for hazardous atmospheres that require explosion proof electrical equipment. They do, however, require a means of separating material from the magnet. To accomplish this, a stripper device may be employed or if the part is positioned and



*Vacuum cup hand*
The vacuum pick-up has the virtues of the magnetic pick-up and is much less susceptible to workpiece side slip. For light- to moderate-weight glass, plastic, ferrous, and non-ferrous parts, the vacuum pick-up is often an excellent choice.



*Simple vacuum cup hand*
Fragile parts such as cathode ray tube face plates (illustrated) are handled easily by a simple vacuum pick-up. The vacuum pick-up has better reliability than the magnetic pick-up: there are well-designed telescoping vacuum lines for long-reach arms.



*Expansion bladder hand*
Large cylindrical vessels with flexible walls are difficult for mechanical hand and fingers to grasp, but an expandable bladder in the form of a cuff will do the job. A rigid back-up ring supports the bladder. The illustrated plastic container with tapered walls represents a typical part for which the bladder is useful. Of course, a given bladder design will handle only one size of vessel. An alternative to the internally expanding (in ID) bladder shown is one which is expanded externally (in OD) after insertion into a vessel. Vacuum pick-up can be another suitable alternative for an application such as this one.

**Figure 3.3** *Some typical vacuum pickup systems* clamped, welded or otherwise secured the magnet can be pulled from the part. The permanent magnet can be designed to produce extremely shallow magnetic penetration, a feature that is valuable when, for example, it is necessary to remove single thin ferrous metal sheets from a stack. In fact, standard designs are available that will lift single sheets as thin as .031 inch.

Another version of a permanent magnet which can be used with sheets is the sheet 'fanner' or separator. This device separates sheets in a pile so a magnetic 'hand' or a gripper can pick up individual pieces. Magnetic induction of the sheets with like polarity causes them to repel each other and to tend to rise in mid-air. As each sheet is taken away the others rise to higher positions.

Regardless of whether the magnet employed is permanent or electro, there are several matters that must be considered before a proper selection can be made. The following are of importance.

1 SHAPE OF PART

Parts having a large flat contact surface are 'naturals' for magnetic handling. Other shapes can be handled, but more compensation must then be made. For example, round pieces tend to roll but this can be prevented by providing pole plates with contoured or irregular surfaces. Any part having relatively high mass in relation to the area presented for magnetic contact will require a stronger magnet to project enough magnetic flux lines into the material to permit lifting.

2 WEIGHT

It is obvious that the lifting capability of the magnet must be great enough to handle the heaviest part to be manipulated. Conditions are seldom perfect, and just as a crane cable or sling must be selected to have some reserve capacity, a magnet must be given the same consideration.

3 TEMPERATURE

Electromagnets of standard design will handle materials having temperatures up to 140°F. Modified designs will accommodate temperatures up to 300°F and special designs can be made for even higher temperatures although cost then becomes more of a determining factor. Most permanent magnets are fully effective if material temperature does not exceed 200°F though others have been designed for handling parts up to 900°F.

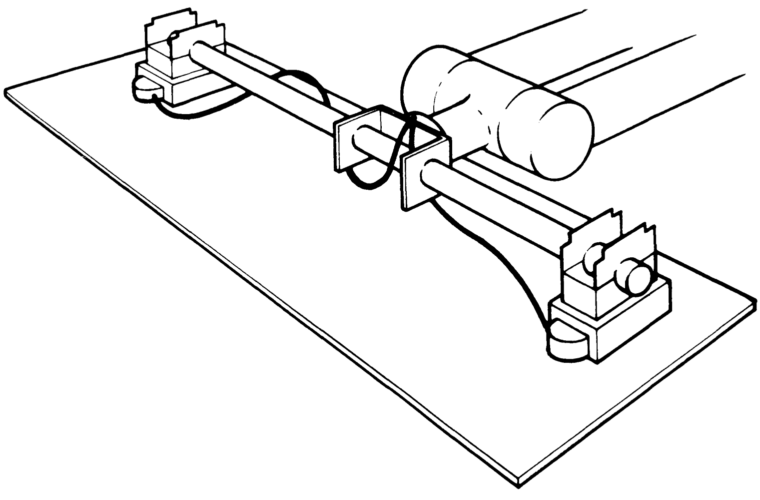
In all cases, frequency and length of contact with the hot part and the length determine most of the operating limits.

4 SURFACE CONDITION

A smooth, flat, dry, clean surface is ideally suited for magnetic parts handling. Irregular or curved surfaces will affect holding power but after compensation has been made for the irregularity, performance is then predictable. However, rust, mill scale, oil, pits and sand can individually or collectively affect holding power in an unpredictable manner so it is advantageous to minimize these conditions as far as possible.

5 POSITION TO BE HANDLED

Lifting, transferring or otherwise handling parts in such a manner that they are directly beneath the magnet is the most efficient way of handling. But having the magnet face in a vertical plane with parts cantilevered only uses a magnet at 25% or less of its maximum potential because the material tends to slide rather than pull away from the face. Some parts held in this position might possess a shape that would create a bending moment which would tend to break the part away from the magnet.



These pickups are good for use on flat surfaces, such as ferrous sheets or plates, and will deal with objects of several sizes. Weight of the part should be no more than moderate so that side slippage is avoided. Positioning for pickup does not need to be precise and 'grasping' is instantaneous, both time savers.

**Figure 3.4** *Typical electro magnet pickup for use with flat surfaces*

As previously stated, the electrical power required for an electro magnet must be D.C. This can be supplied by batteries, engine or motor driven generator sets or rectified A.C. Batteries offer the greatest portability but are the most limited in capacity. Many plants have generators to supply D.C. for other operations so often there is a ready source available. If it is necessary to resort to rectified A.C., this poses few problems since rectifier design is constantly improving and the present costs of such a system are not prohibitive.

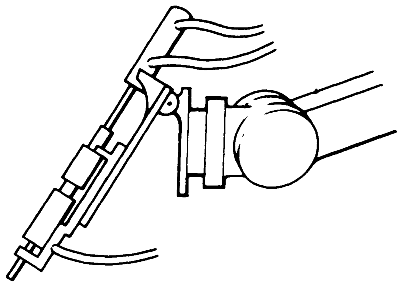
A typical electromagnetic pickup designed for use with flat surfaces is illustrated in Figure 3.4.

## Tools

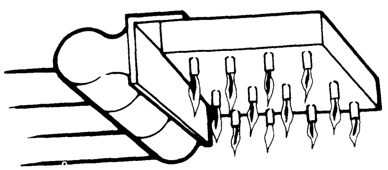
With various grasping and pickup devices, robots clumsily imitate what a human operator might do. Sometimes the human is directed to pick up a tool and use it continuously. When a robot takes over such a task the tool might just as well be fastened to the robot's extremity permanently. Or, if the robot has two or more tools to choose among, then quick disconnect selection of tools may be in order.

Apart from peculiar mounting characteristics, tools fastened to robot wrists are likely to be given the same capabilities they would have had if they were manually manipulated. Therefore, the concept needs only to be documented with examples of tools affixed to robot wrists.

A range of such tools is illustrated in Figure 3.5.

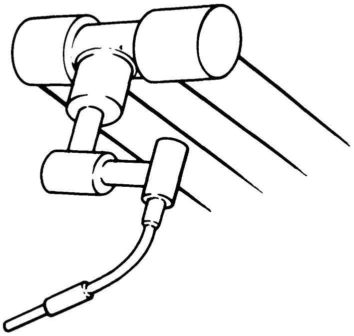


*Stud-welding head*
Equipping an industrial robot with a stud-welding head is also practical. Studs are fed to the head from a tubular feeder suspended from overhead.

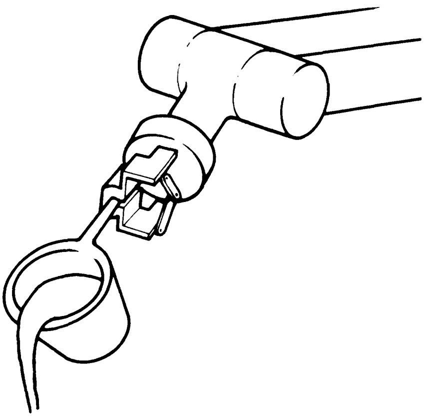


*Heating torch*
The industrial robot can also manipulate a heating torch to bake out foundry molds by playing the torch over the surface, letting the flame linger where more heat input is needed. Fuel is saved because heat is applied directly, and the bakeout is faster than it would be if the molds were conveyed through a gas-fired oven.

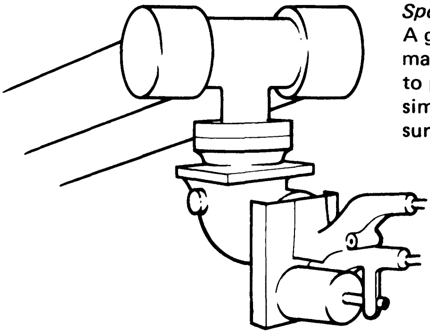
**Figure 3.5** *Examples of tools fastened to robot wrists*



*Inert gas arc welding torch*
Arc welding with a robot-held torch is another application in which an industrial robot can take over from a man. The welds can be single- or multiple-pass. The most effective use is for running simple-curved and compound-curved joints, as well as running multiple short welds at different angles and on various planes.

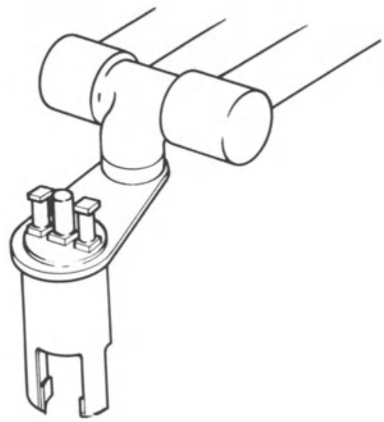


*Ladle*
Ladling hot materials such as molten metal is a hot and hazardous job for which industrial robots are well-suited. In piston casting, permanent mold die casting, and related applications, the robot can be programmed to scoop up and transfer the molten metal from the pot to the mold, and then do the pouring. In cases where dross will form, dipping techniques will often keep it out of the mold.

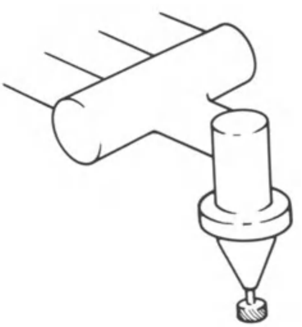


*Spotwelding gun*
A general purpose industrial robot can maneuver and operate a spotwelding gun to place a series of spot welds on flat, simple-curved, or compound-curved surfaces.

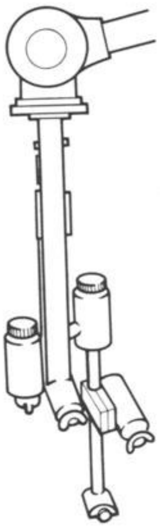
*Figure 3.5 (continued)*



*Pneumatic nut-runners, drills and impact wrenches*
General purpose industrial robots are especially well suited for performing nut-running and similar operations in hazardous environments. Drilling and countersinking with the aid of a positioning guide is another application. Mechanical guides will increase the locating accuracy of the robot and also help shorten positioning time.

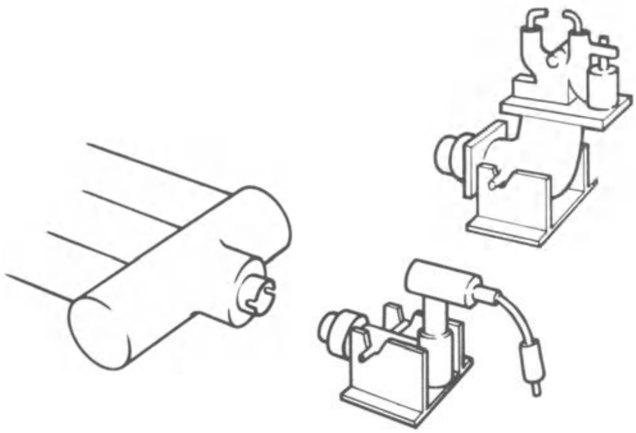


*Routers, sanders and grinders*
A routing head, grinder, belt sander, or disc sander can be mounted readily on the wrist of an industrial robot. Thus equipped, the robot can rout workpiece edges, remove flash from plastic parts, and do rough snagging of castings.



*Spray gun*
Ability of the industrial robot to do multipass spraying with controlled velocity fits it for automated application of primers, paints, and ceramic or glass frits, as well as application of masking agents used before plating. For short or medium-length production runs, the industrial robot would often be a better choice than a special-purpose setup requiring a lengthy change-over procedure for each different part. Also, the robot can spray parts with compound curvatures and multiple surfaces.

*Figure 3.5 (continued)*



*Tool changing*
A single industrial robot can also handle several tools sequentially, with an automatic tool-changing operation programmed into the robot's memory. The tools can be of different types or sizes, permitting multiple operations on the same workpiece. To remove a tool, the robot lowers the tool into a cradle that retains the snap-in tool as the robot pulls its wrist away. The process is reversed to pick up another tool.

*Figure 3.5 (continued)*

*Chapter 4*

# Matching robots to the workplace

Robotizing a process might mean anything from the purchase of a single robot to replace one man at an existing machine to the design and implementation of a complex manufacturing system using several robots, all controlled from a central computer. Even in the very simplest case, there is more to consider than choosing the best robot for the job, asking the existing man to step aside, and setting the robot to work in place of him. In this chapter some of the practical aspects of the robot-to-machine interface are examined. While it is soon found that special provisions must be made to compensate for the robot's inability to see and feel, there are many opportunities for cashing in on some of the non-human – even superhuman – properties of our mechanical imitators. Intelligent production engineering and system design should seek to explore ways and means for taking full advantage of the robot's capacity for working continuously, accurately, and reliably under hostile conditions – not forgetting that work can sometimes be arranged with one robot tending two or more machines in a work sequence that would quickly have a human completely worn out.

## Part orientation

Whatever the size of the system, and whether there is just one robot or a whole battery of them, one of the things to get sorted out right from the start is the physical position and attitude of the workpiece at the front end of the work station. It would be no good at all, for instance, simply to pile a batch of parts in a random heap in a tub or tote box, dump the lot down, and expect the robot to be able to pick out the parts one by one in a sensible, repeatable gripper-to-part relationship, at least not with technology in its present state of development. All that the robot could do would be to grope blindly at the pile of parts, with a chance that one or more might be picked up, but with no chance at all that any part would ever be gripped in the position and attitude necessary for it to be fed to the next stage of the process.

The solution adopted must obviously be suited to each case, since it will depend on the particular manufacturing operation and the relative dispositions of all the related items of plant. Some discussion of this problem is undertaken in the case histories which form Part II of this book. Whatever the method, things have to be arranged so that the robot can be taught to pick up the first part of a batch correctly, after which all the other parts in the batch are presented to the robot hand at the same pickup point, in the same attitude, or at least in a series of known attitudes. Palletization often provides a suitable answer. Parts can be located on a spigot, or between guides. Sometimes parts can be arranged on a pallet in a grid pattern, and the robot must then be taught to recognize this pattern and pick up the parts in sequence until the pallet has been emptied. Discs can be set up in a neat vertical stack from which the robot plucks them one by one, using vacuum cups instead of gripper fingers. In molding, die casting, and similar processes part orientation is far less of a problem for the simple reason that each new part is made in exactly the same place, and in precisely the same attitude.

Part orientation is not just a matter of knowing where the workpiece is to be found when the robot picks it up for the first time. Consider, for example, the common arrangement for quenching die castings by dropping them into a bath of cold water. This may be an obvious and convenient way of cooling the castings when a man is operating the machine, but it is by no means so clever when a robot is doing the job. If the robot is expected to take the raw castings from the quench tank and load them into a trim press, it is going to look pretty silly fishing for them in the water where their position and orientation is anybody's guess. The answer in this case is to make the robot grasp the part, take it from the mold, dip it into the water tank, and *without letting go,* load it into the trim press. Although this means that the work has had to be adapted to recognize the robot's shortcomings, full advantage has been taken of the fact that robot hands can grip parts that would be too hot for a man to handle.

So far, the examples given have all been concerned with the loading or operation of machines. In other applications, such as the welding of car bodies, the work is brought to the robot on a conveyor, stopped while the robot does its job, after which the conveyor steps on to bring the next body into position. Part orientation is determined only by the accuracy with which each body is located on the conveyor system. In such stop-go conveyor arrangements, the conveyor speed is matched to the slowest operation along the line and each movement of the conveyor is triggered from a central control system. More complicated is the process where the work is offered to the robot on a conveyor which does not stop, but which causes the workpiece to be carried slowly past the robot station. Moreover, the speed of such conveyors may be variable, to suit progress achieved at other stations along the line. The complex problems which this creates for the robot are overcome with the aid of instrumentation which senses the conveyor speed and which can signal the exact position of the workpiece to the robot's own command system.

There is significant work underway to provide robots with some rudimentary sensory perception—visual and tactile. When these attributes become available there will be less insistence upon absolute preservation of orientation. For now, however, in any robotized manufacturing system the rules should be:

– Arrange for part orientation to be defined at the pickup point.
– Once the process has started, never allow part orientation to be lost.
– Never drop a part!

### Interlocks and sequence control

In order to establish a good working relationship between the robot and its associated plant, interlocks and sensors have to be provided that replace the ears, eyes, nose and hands of the human worker. Such devices are needed to initiate each stage of the production cycle at the right time, and to prevent damaging or dangerous movements of any part of the robot or plant. Thus, the conveyor must not start up before the robot has removed a part clear of the delivery station. It is obviously desirable that a robot arm is not placed between the closing jaws of a press. Has the robot really removed all the casting from the die casting mold or are some broken pieces still trapped in there waiting to cause havoc when the next cycle starts? Production engineers starting up a new robotized work center have to weigh up all the normal requirements of the process, then consider possible malfunctions which need special interlocks or sensors to protect the hardware, and the entire control system must be designed to fit the robot into the workplace in a sensible, integrated fashion.

Fortunately, there is no shortage of mechanical, electrical and electronic devices that can be built into a total control system. Designing these controls and interlocks is within the competence of any process control engineer used to working with automated machinery. In robotics, the engineer finds a slightly different situation from designing the custom-built type of work station because he must find ways and means for fitting sensing devices, limit switches and the like, to standard machinery that was intended for operation by human hands. Such modifications are seldom difficult, but their introduction should not in any way prevent the general purpose machinery in the system from being redeployed elsewhere in the future or make it difficult for the machinery to revert to manual operation should the robot be out of service. Some suggestions follow.

*Mechanically operated limit switches:* clamped to machine slides, conveyors or to any other place where the position of a moving part is critical to starting or stopping the robot sequence.

*Microswitches:* useful in conjunction with end stops to act as limit switches or to sense the weight of parts stacked on a pallet. For example, a pallet can be arranged to sit on a spring-loaded platform, so that when the workpiece is in place on the pallet, the platform is depressed sufficiently to operate a strategically placed microswitch underneath.

*Photoelectric devices:* capable of sensing the presence of any object, provided that the object is opaque, when the object interrupts a beam of light.

*Pressure switches:* arranged to monitor the pressure of air lines or hydraulic feeds. For example, the pressure could be monitored at the cylinder of a fixture clamp, so that the robot could be signalled when the clamping pressure released and the workpiece was ready for extraction.

*Vacuum switches:* arranged so that if the robot is operating with a vacuum type pick up unit, the robot does not move from the pickup position until a vacuum is indicated.

*Infrared detectors:* capable of detecting the absence or presence of hot workpieces. These are particularly useful in such applications as die casting and forging. Infrared detectors can also be used to check that parts are at the correct temperature for the process.

*Signals from other electronic control systems:* a most important source of sequencing information. These sources might be NC machines, other robots, or a computer arranged as a master controller for the entire manufacturing system.

Since it is possible both to send and receive signals to and from the associated equipment and also to utilize this information at any desired point in the robot program, the robot now has the ability to accept complete control over any required sequence of operations. An additional advantage is that the sequence of operations may be varied automatically depending upon the information received from the associated equipment.

The alternative sequences required will vary from application to application and from the simple to the complex. In the majority of applications the variable sequence may be controlled by information given to the robot by simple limit switches, proximity detectors, etc.

*Outline example of a sequence control problem*

In a typical application the robot is required to interface with two incoming conveyors, two pallets, two safety doors and a reject position. The requirements are that the robot should pick up parts from conveyor A and load pallet A, pick up from conveyor B and load pallet B. After pickup from either conveyor, the parts are presented to a detector located at each conveyor. The detectors give a GO/NO GO signal. Should a NO GO (reject) signal be received, the parts from either conveyor are placed at the common reject position.

Since each pallet is loaded with 8 layers at 5 parts per layer, the robot memory must also have the capability to memorize how many parts and in what position the last part was loaded on each pallet.

Other requirements of this application are:

1 While parts are present at each conveyor the robot must alternate between conveyors.
2 If parts are present on only one conveyor or there are parts present on both conveyors but with a 'queue' indicated on one conveyor, then the robot must give priority to the most loaded conveyor. That is, either the conveyor with parts available or, alternatively, to clear the queue.
3 Should there be a queue on both conveyors the robot must alternate until such times as one queue is cleared and then revert to priority on the other conveyor.
4 Should the reject position become full and the robot has a reject part, then the robot must stop until space is available.
5 Having fully loaded either pallet the robot must revert to loading the remaining pallet. Should both pallets be fully loaded the robot must stop.
6 When an empty pallet replaces a fully loaded pallet the robot must automatically recognize the condition on each conveyor and revert to alternate or priority.

The sophisticated industrial robot with a large memory and with the ability to digest a range of inputs and dispense a range of outputs can cope with an almost bewildering spectrum of alternative actions — so long as all possibilities have been anticipated by the system designer.

*Detailed analysis of setting up a sequence control system*

This example is drawn from a real-life report* submitted in the automobile industry and presented here in its authentic form.

*This section, including Figures 4.1, 4.2, 4.3 and 4.4, has been extracted with slight modifications from Dennis W. Hanify and Jay V. Belcher, *Industrial robot analysis – working place studies* (Proceedings 5th International Industrial Robot Symposium, Sept, 22-24, 1975, Chicago, Ill.), published by the Society of Manufacturing Engineers, Dearborn, Mich., 1975, to whom due acknowledgement is expressed.

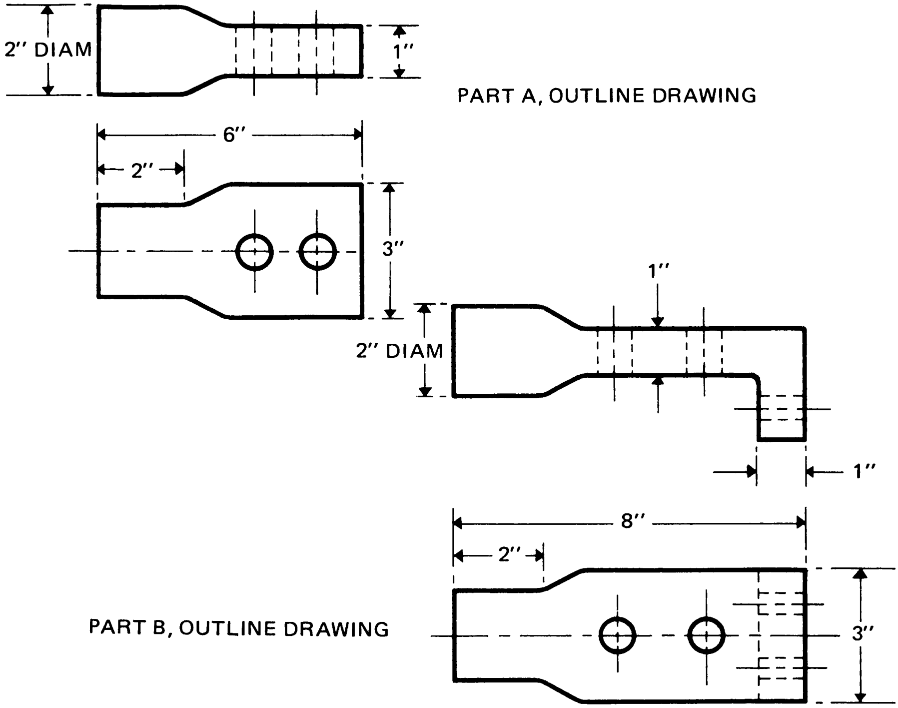



**Figure 4.1** *Sequence control example: the workpieces*

Two different workpieces are to be manufactured at the workplace. They are very similar in shape and the machining operations are the same for both pieces. Workpiece outline drawings appear in Figure 4.1. Each workpiece weighs approximately 1.82 Kg. The material is an aluminum alloy forging. Workpiece feed positions are shown for each machine in Figure 4.2. Machining is done on the hub of each part.

MATERIALS HANDLING SEQUENCE

The previous machining operations are automated and at the completion of the machining cycle the part will be manually placed in a holding fixture, properly oriented and ready for the subsequent machining cycle. The sequence of this machining cycle is:

1 Part is removed from the holding fixture and moved to Machine A.
2 The part is then inserted into the clamping fixture on Machine A and the machining cycle started.
3 After the automatic machine cycle, the part is moved to Machine B.
4 Part is inserted into the clamping fixture of Machine B and the automatic machining cycle started.
5 After completion of the automatic cycle the part is moved to Machine C.

6 Part is inserted into clamping fixture of Machine C and the automatic cycle started.
7 After completion of the automatic cycle the part is moved to Machine D.
8 Part is inserted into the aligning and clamping fixture and the automatic cycle started.
9 After completion of the automatic cycle the part is moved to Machine E.
10 Part is inserted in the holding fixture and the machine cycle started.
11 After completion of the cycle the part is loaded in a tote bucket or rack for disposition.

Part positioning for inserting in the machine fixtures is also shown in Figure 4.2. A maximum positioning error of not greater than 1.6 mm is required. The machine fixtures have been designed to allow this tolerance and still maintain the machining accuracy required.

### ANALYSIS OF THE MACHINING CYCLE

The production machines involved in this study are sufficiently automated to be used with an industrial robot. The fixtures used with these machines provide the required degree of automation for clamping and aligning the part.

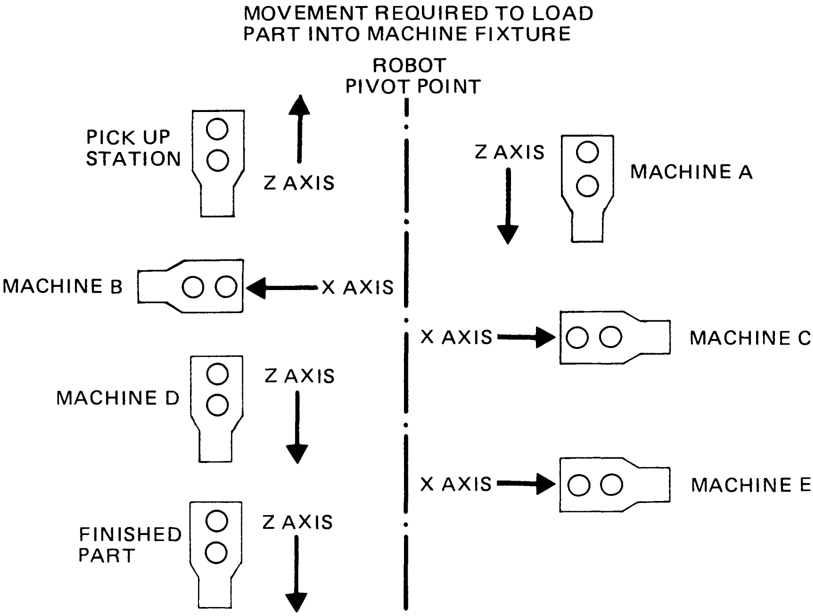



**Figure 4.2** *Sequence control example: workpiece feed positions*

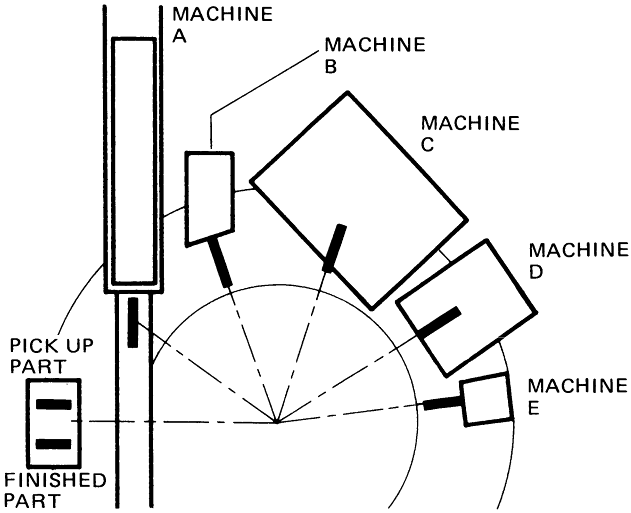



**Figure 4.3** *Sequence control example: equipment layout*

Since the machine tools involved in this study are flexible in their placement, the machining sequence should be kept in mind and the machines located in a logical sequence of machining operations. A typical layout is shown in Figure 4.3. This type of layout permits the part to be transferred from one machining operation to the next in the correct sequence. The layout eliminates wasted robot movements and minimizes cycle time.

The maximum cycle time allowed for the five machining operations is 1 minute 45 seconds to 2 minutes. This period of time is dictated by the previous operation and by the requirement of 1200 parts per week, which is 30 parts per hour on a one-shift basis. The cycle times which include clamping, machining and unclamping for each machine are:

| | |
|---|---|
| Machine A: | 11 seconds |
| Machine B: | 6 seconds |
| Machine C: | 20 seconds |
| Machine D: | 15 seconds |
| Machine E: | 10 seconds |

INTERLOCKS ANALYSIS

When interlocks are properly used and are of sufficient number, costly collisions, jam-ups, scrap parts, and costly damage to the robot and equipment can be prevented. The following list of interlocks represents the minimum number required in this example and can be expanded as desired or as the equipment permits.

*Pickup station*

Signal to robot that a part is present.

*Machine A*
Signal to robot that fixture clamp is open.
Signal to robot that fixture is empty.
Signal to robot that fixture clamp has closed.
Signal to robot that machine cycle is complete.

*Machine B*
Signal to robot that fixture clamp is open.
Signal to robot that fixture is empty.
Signal to robot that fixture clamp has closed.
Signal to robot that machine cycle is complete.

*Machine C*
Signal to robot that fixture clamp is open.
Signal to robot that fixture is empty.
Signal to robot that fixture clamp has closed.
Signal to robot that machine cycle is complete.

*Machine D*
Signal to robot that fixture clamp is open.
Signal to robot that fixture is empty.
Signal to robot that fixture clamp has closed.
Signal to robot that machine cycle is complete.

*Machine E*
Signal to robot that fixture clamp is open.
Signal to robot that fixture is empty.
Signal to robot that fixture clamp has closed.
Signal to robot that machine cycle is complete.

Signals from the robot to the machines are also important for automatic operation. These three signals are applicable to all machines: close fixture clamps; start machining cycle; and open fixture clamps.

GRIPPING REQUIREMENTS

The gripping technique required is a dual gripper design. This type of gripper permits handling two parts at a time so that a part may be removed from a machine and the new part inserted without excessive motions of the robot and a loss of cycle time. Rubber pads should be used on the fingers to give some compliance and protect the part finish.

In designing the gripper it must be kept in mind that two different parts must be handled and the same program should be used for both parts. This permits parts to be intermixed in the machining operation.

## Workplace layout

Work configurations can be classified in the following four ways:

1 Arranging work around the robot
2 Bringing work to the robot
3 Work travels past the robot (a variant of 2)
4 Robot travels to work

Naturally each configuration is appropriate for different manufacturing operations or systems of work organization. One of the early decisions in the installation process is to establish an optimal working layout.

*Arranging work around the robot*

All early installations were of the first class, because this involved the least commitment and the least plant disruption for the oft-times skeptical pioneer user. In die casting, for example, the first tentative step was to put the robot in front of the already-installed die casting machine and let it extract and quench the casting. Since the robot had time on its hand, it was not a very bold step forward to bring in a trim press, put it in reach of the robot, and let the robot operate both machines. When, as is often the case, a second die casting machine is close at hand, it may be practical to have just one robot unloading two die casting machines, quenching trimming and stacking the output of both, an evident illustration of the 'surrounded by work' class of operation. See Figure 10.4 in Part 2 of this book.

In loading and unloading metal cutting machines, cutting times are often such that one robot can attend to a group of machines. A logical layout for the polar coordinate robot arm is to group the machine tools around the robot, within its sphere of influence. This 'surrounded by work' installation remains the most prevalent in the field. Such jobs as forging and trimming, press to press transfer, plastic molding and packaging, and investment casting are other examples of the class.

*Work travels past the robot*

The addition of computer control to an industrial robot produces tremendous flexibility. For example, the robot can be made to track a workpiece which is being carried on a conveyor, performing its task as the job passes by – see Figure 4.4. The versatility of such a system can be extended to cope with variations in the conveyor speed.

The following description* describes the systems by which line tracking with an industrial robot can be accomplished.

MOVING-BASE LINE TRACKING

With this method, the robot is mounted on some form of transport system, e.g. a rail and carriage system, which moves parallel to the line and at line speed. This method requires the installation of the transport system which may not be possible or economical. If multiple robot systems are set up adjacent to one another alongside a moving line,

*This section, including Figures 4.5 and 4.6, has been extracted in slightly modified form from the paper *Moving line applications with a computer controlled robot,* by Bryan L. Dawson, Applications Engineer, Cincinnati Milacron, SME Technical Paper MS 77-742, published by the Society of Manufacturing Engineers, Dearborn, Mich., 1977, with due acknowledgement to author and publisher.

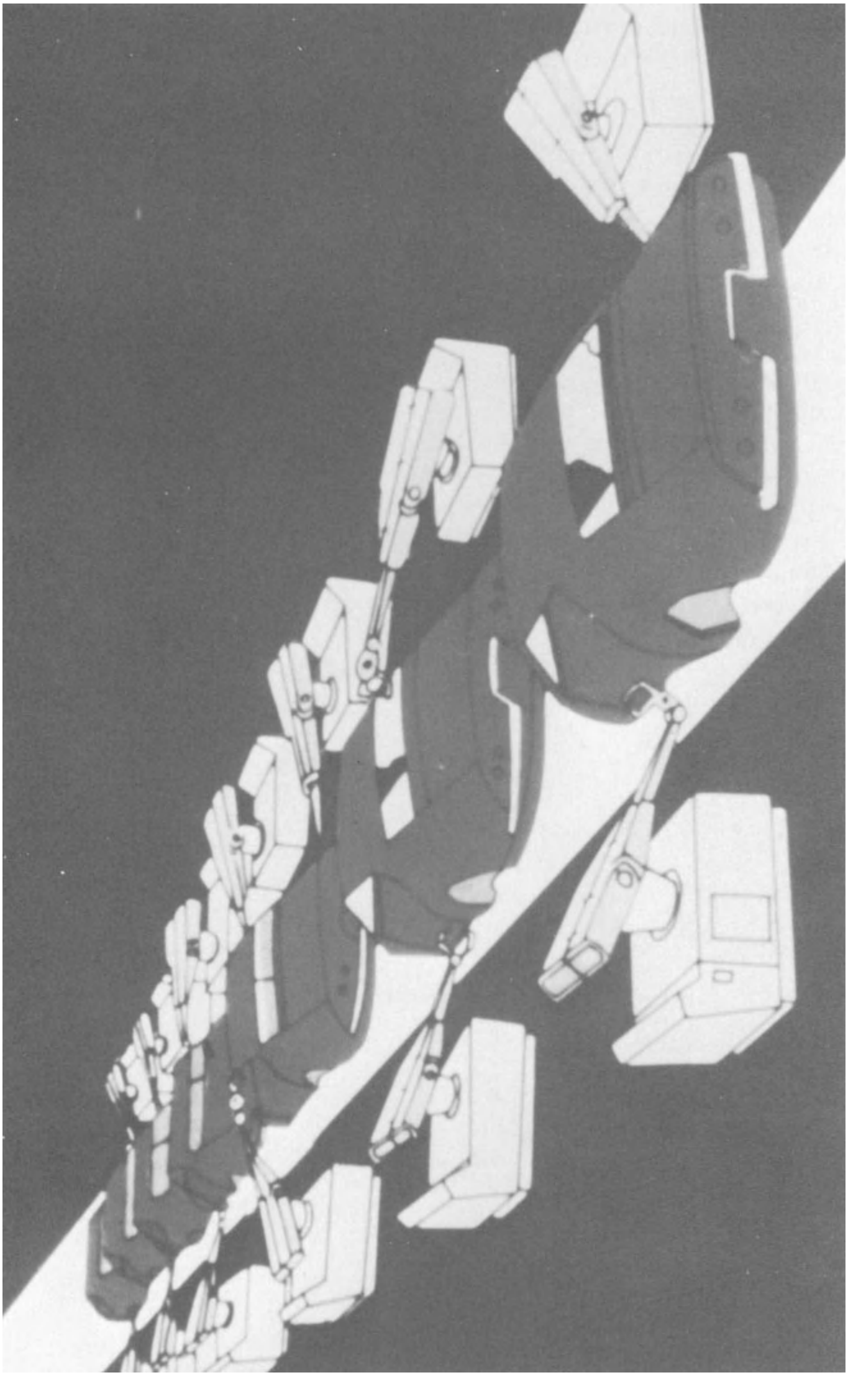


**Figure 4.4** *Work comes to robot*

there may be interference problems between adjacent stations. A powerful drive system is required for each transport device in order to return the robot back to its starting point from the other end of its tracking range in the fastest possible time.

2. STATIONARY-BASE LINE TRACKING

In this method of line tracking, the robot is mounted in a fixed position relative to the line. Hence the name 'stationary-base'. This naturally constitutes an economical installation which requires less maintenance than is necessary with moving-base systems.

Full tracking capability of the robot allows it to perform its taught program on a part moving through its station, irrespective of the speed or position of that part. The positions of taught points, the orientation angles of end effectors around taught points and the velocities of motions between taught points will have the same values, *in relation to the part*, system of the computer controlled robot allows the full tracking capability to be easily implemented. Positions of taught points are stored in memory as coordinates in space and not as robot axis coordinates. The layout of the system is summarized in Figure 4.5.

During the teaching operation the part is moved to a convenient position in front of the robot and stopped. Points are taught as normal but each coordinate in the direction of the line is modified by an

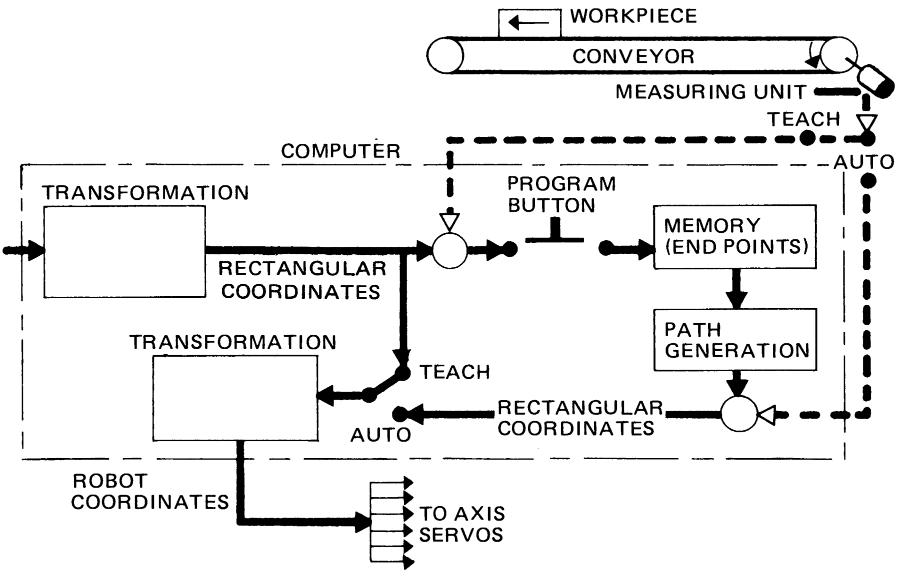



**Figure 4.5** *Work travels past robot – diagram of tracking and control system*

amount equal to the current position sensor reading, prior to being stored in memory. Thus, the stored data are referenced to the start point of tracking. If it is desirable, for more convenient access, the part may be repositioned at any time during the teaching operation.

In the automatic mode of operation, the stored points are used to generate the desired paths, which are then modified by the current position sensor reading. In this way, the control, in effect, changes the coordinates of taught points in the tracking direction by an amount equivalent to the distance between the position of the part at which the point was taught and the position of the part where the point is replayed.

### IMPLEMENTATION OF STATIONARY-BASE LINE TRACKING

The requirements for a typical robot installation to be used for a stationary-base line tracking application are:

1 A position sensor connected to the part of conveyor to indicate the position of the part. This sensor is electrically interfaced with the control.
2 A limit switch or other form of sensor which is actuated when the part is in a predefined position. This sensor signal, called 'Target In Range', indicates to the control to start to use the information provided by the position sensor to update the position of the part.
3 A series of limit switches or sensors which indicate to the control the style of part on which the robot is to operate. This permits the control to select the correct branch program for that part from its memory. These switch or sensor signals use a simple binary code to allow the control to select one of 15 different branch programs.

### CONSIDERATIONS FOR STATIONARY-BASED TRACKING APPLICATIONS

If a sequence of operations to be performed on a stationary part is taught to a robot, the robot will replay the programmed points at the same positions, in space, at which they were taught. The points will always be within the range of the robot arm during replay because it is impossible to teach a point that is outside that range. However, when a robot is working on a continuously-moving part, taught points on the part that were within the range of the robot during the teaching operation may, due to a variety of circumstances, be outside that range during replay. Points that were taught with the part at one end of the range could be replayed with the part at the other end of the range. Hence, because the robot will not be replaying programs with modified paths between modified programmed points, there are certain considerations to be taken into account in the planning and programming of moving line tracking applications with a stationary-base robot. These are discussed in the following text.

*Tracking window.* The diagram in Figure 4.6 illustrates the robot's large tracking range, when used in tracking applications in which the Y axis of the robot is set parallel to the moving line. As the diagram indicates, there are many parameters that influence the length of working range of the robot in the direction parallel to the moving line. This working range of the robot parallel to the line is termed the 'tracking window'. The height of the part on the conveyor, the distance of the robot from the conveyor and the length and configuration of the end effector all play a part in determining the tracking window. Therefore, every tracking application must be considered separately in order that the robot is positioned correctly, relative to the conveyor, to ensure the optimum tracking window.

Once the tracking window for a given sequence of operations has been established, it is entered into the memory of the control. The tracking window basically defines in memory the two limits in the tracking direction beyond which the robot will not attempt to reach. More than one tracking window may be defined for different segments of a tracking operation.

Abort branches and utility branches are available in software. They ensure that, when the robot is working with a moving line, logical decisions and actions are made by the control to take corrective action in response the occurrence of random but foreseeable events. As with non-tracking applications, other interface signals between the robot and the peripheral equipment are easily implemented to ensure that corrective action is taken by the robot in response to other occurrences.

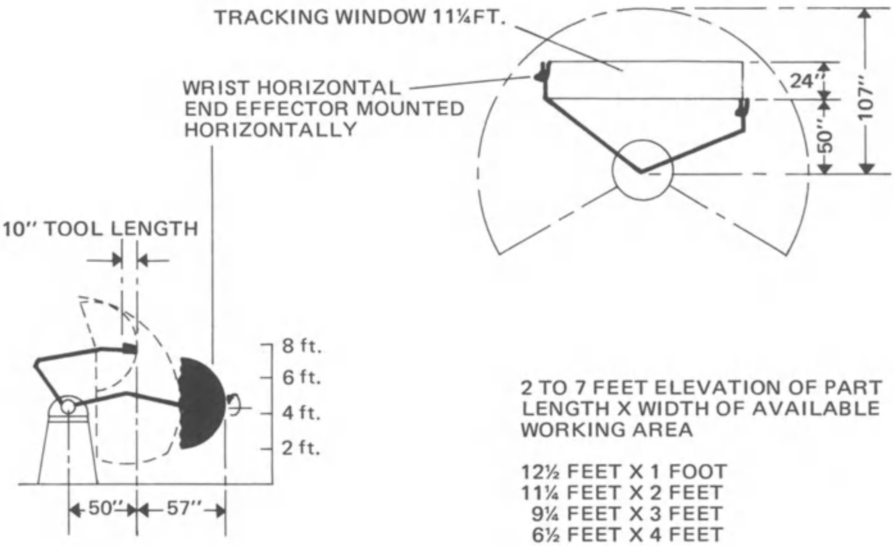



**Figure 4.6** *Work travels past robot – examples of tracking windows*

*Robot travels to work*

When machining cycles are particularly long, a robot can be mounted on a track to enable it to travel among more machines than can conveniently be grouped around a stationary robot. Figure 4.7 is a photograph of a track mounted robot that handles eleven different machine tools. In this example, a buffer station is carried with the robot for parts in intermediate stages of completion.

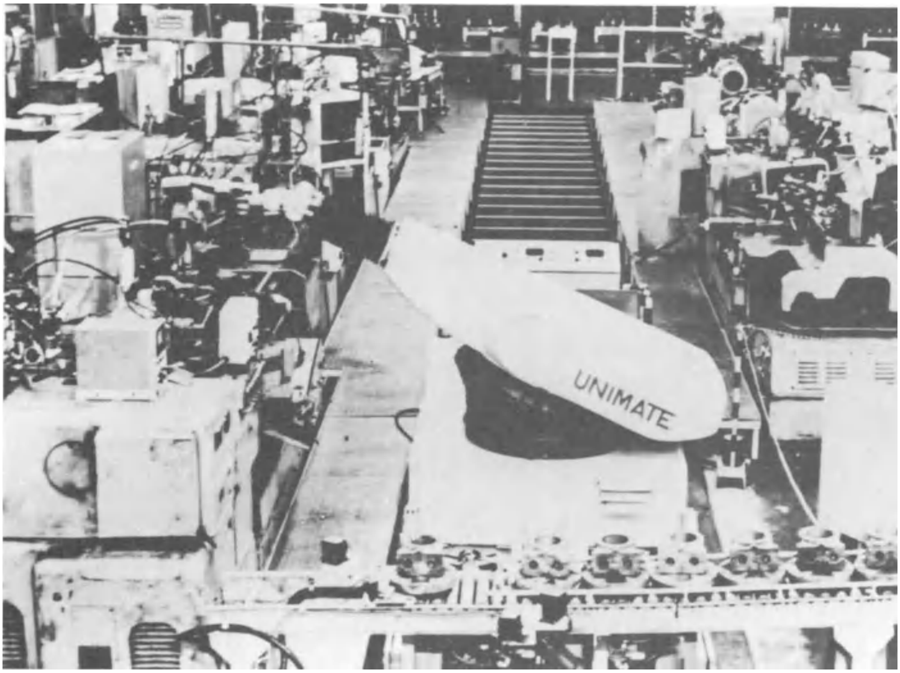



**Figure 4.7** *Robot travels to work – track mounted robot serving 11 machine tools*

In Figure 4.8 a robot is shown which travels overhead to service eight NC lathes. This installation is controlled by a central computer, which instructs the lathes and the robot. The control room contains a library of machining programs for the lathes, as well as for all the possible loading and unloading programs used by the robot. The central computer also choreographs the travels of the robot up and down the line to minimize individual lathe downtime. The line is 200 ft long. Figure 4.9 is a schematic representation of the system.

The system is more fully described in Part II, chapter 19.

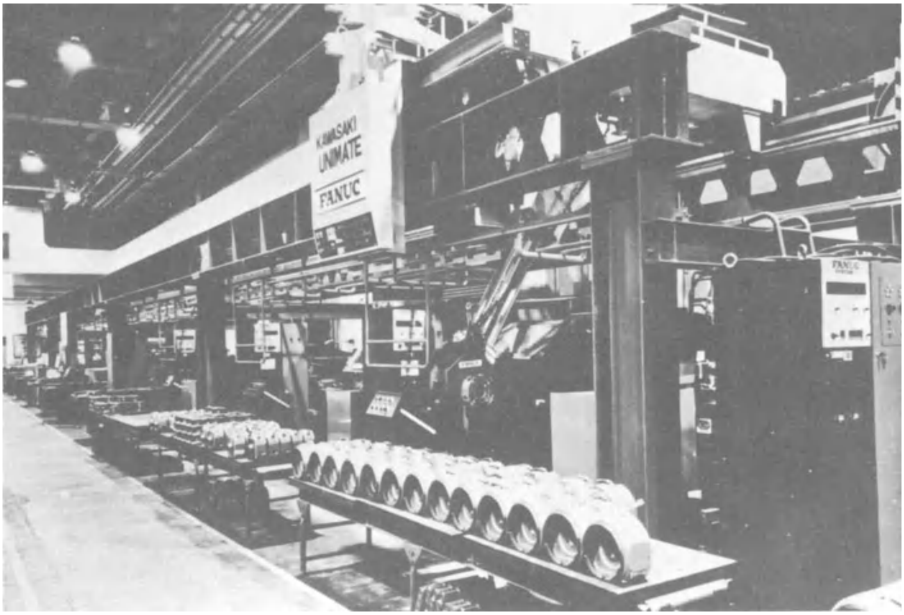



**Figure 4.8** *Robot travels to work – overhead robot serving eight NC lathes*

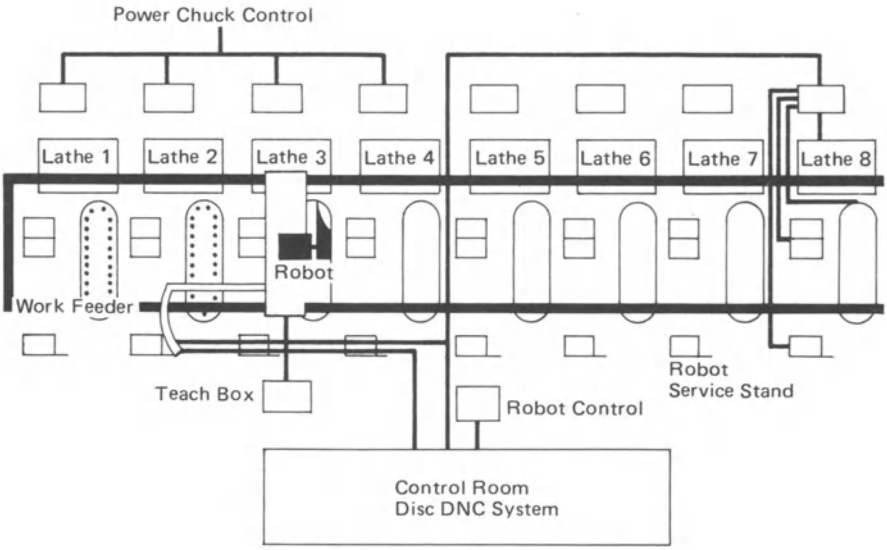



**Figure 4.9** *Robot travels to work – diagram of overhead robot system portrayed in Figure 4.8*