RME40003 Robot System Design

1.0 Fundamentals of Robotics

1.1 Definition of a Robot

A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions, for the performance of a variety of tasks.

1.2 Use of Robots – Advantages

1. Reduction of labour costs
2. Increased quality of products
3. Increased output

1.3 Classification of Robots

(a) Physical configuration
(b) Drive System
(c) Type of control

(a) Physical Configuration

1. Cartesian coordinate type
2. Cylindrical coordinate type
3. Polar coordinate type
4. Revolute coordinate type
5. "Scara" type

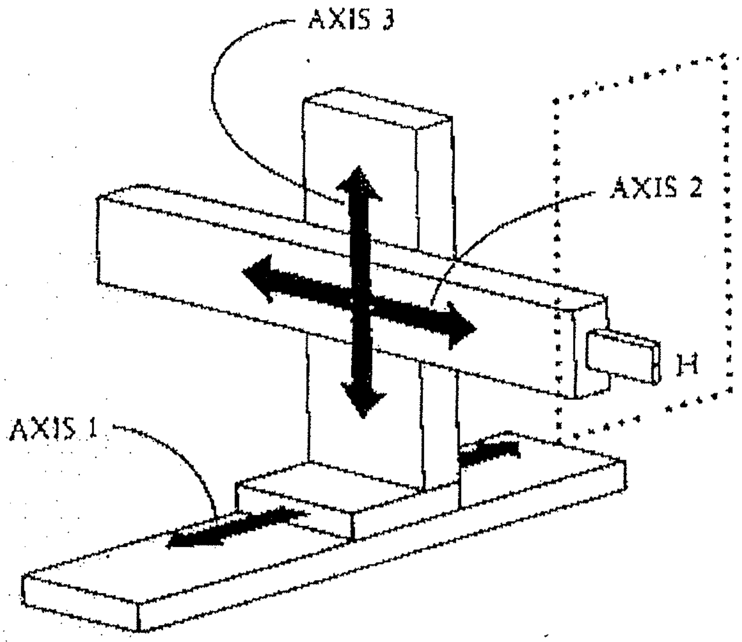


Figure 1.1
Rectangular Coordinate Robot

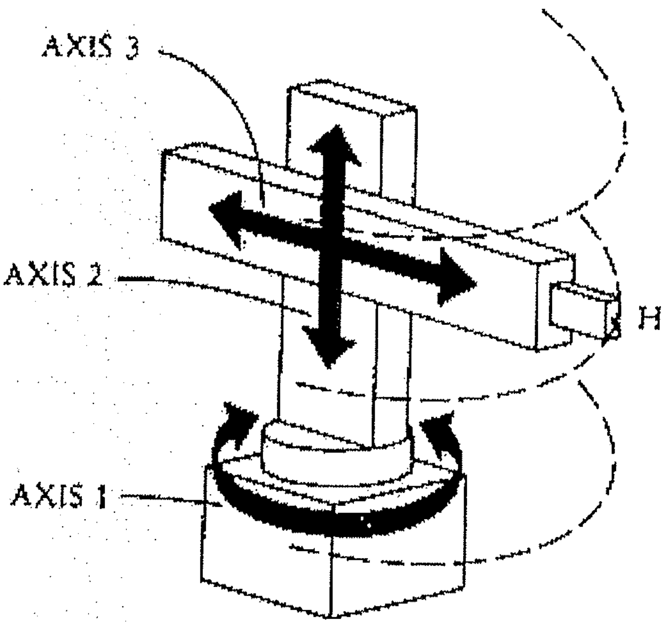


Figure 1.2
Cylindrical Coordinate Robot

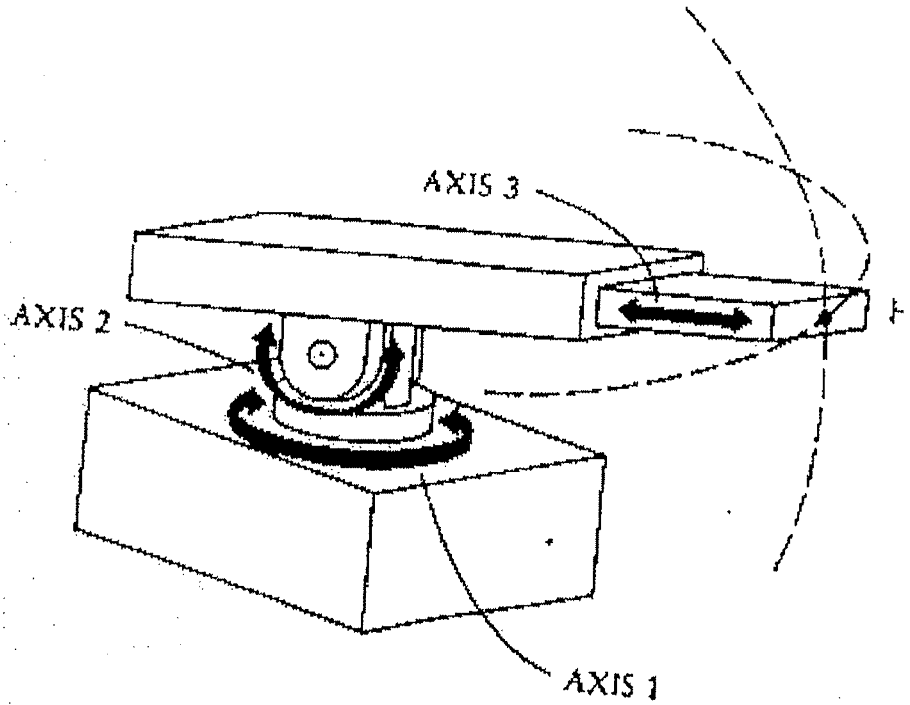


Figure 1.3
Spherical Coordinate Robot

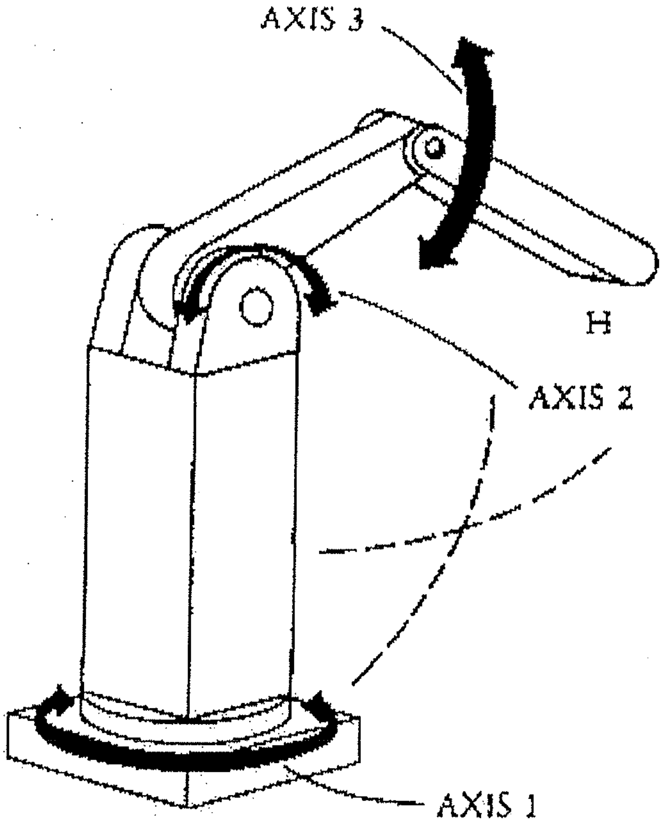
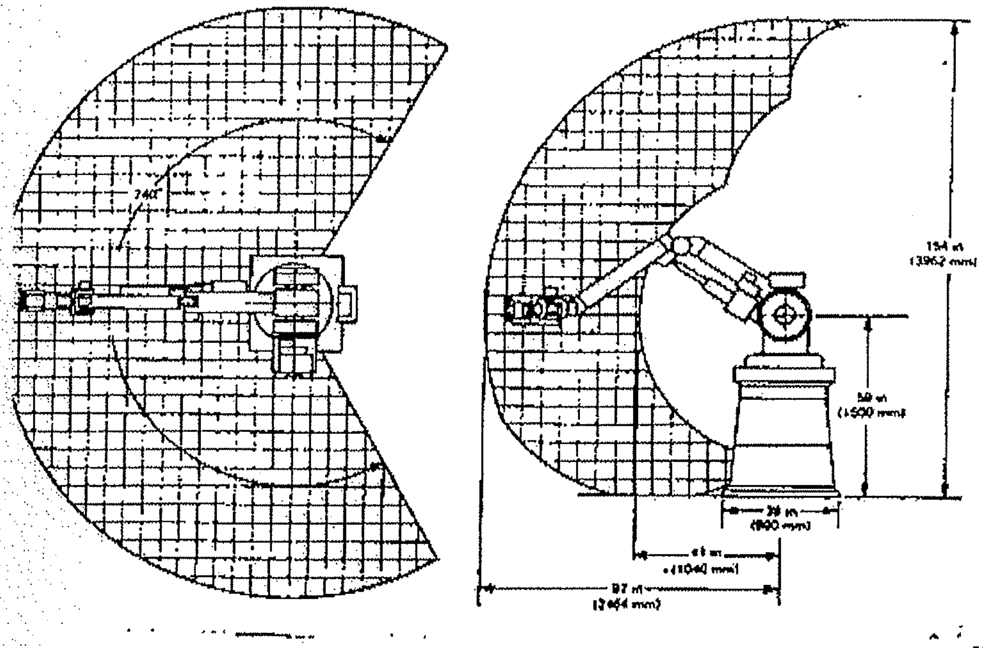
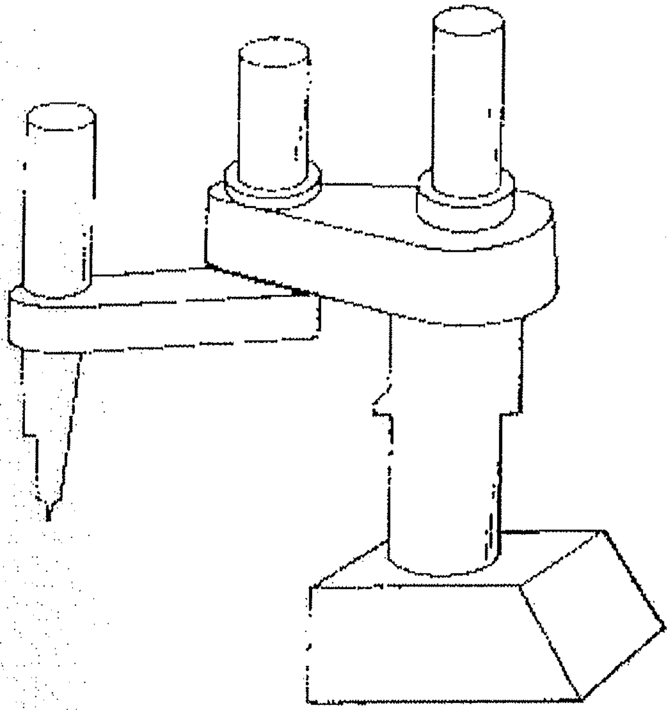


Figure 1.4
Jointed Arm Robot

JOINTED ARM - REACH FLEXIBILITY





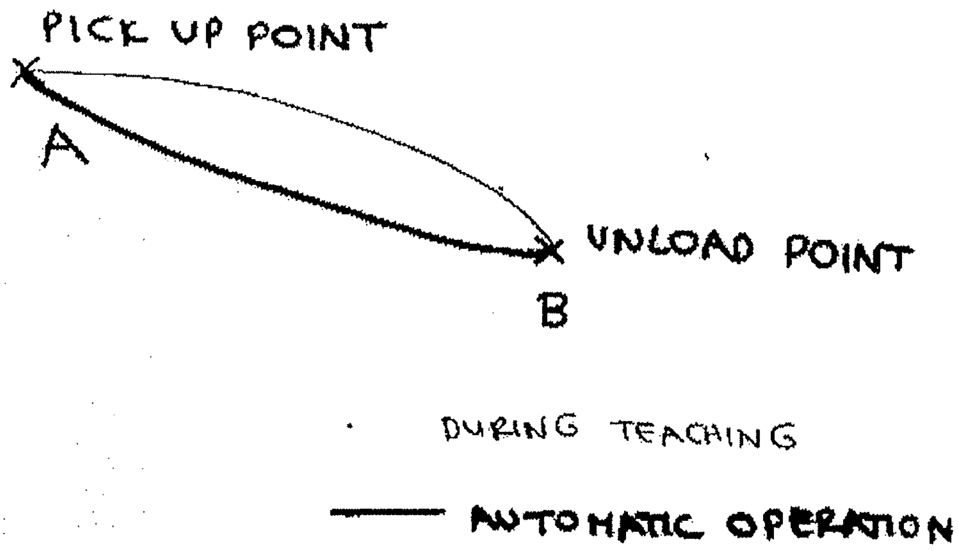
SCARA manipulator

(b) Drive System

a. Pneumatic drive Robots
b. Electric drive Robots
c. Hydraulic drive Robots

(c) Type of Control

a. Point to point Robots
b. Continuous path Robots



1.4 Programming Industrial Robots

(a) Walkthrough method
(b) Leadthrough method
(c) Offline programming method

1.5 Robot Characteristics

(a) Repeatability
(b) Accuracy
(c) Degrees of freedom (D.O.F.)

1.5.1 Repeatability

Repeatability is a measure of a robot's ability to return to a location previously recorded using either the Leadthrough or Walkthrough method of programming

1.5.2 Accuracy

Accuracy is a measure of a robot's ability to reach a location specified using an offline programming method

1.5.3 Degrees of Freedom (D.O.F.)

Degrees of freedom of a robot equals the number of independent joints in its structure

1.6 Choosing a Robot

(a) Cycle time
(b) Payload
(c) Repeatability

(d) Work envelope
(e) Memory capacity
(f) Type of control
(g) Programming skills required
(h) Technical backup
(i) Cost

1.7 Robot Applications

- Replace humans in hazardous work environments
- Maximise use of Robot capabilities
- Maximise Robot utilization
- Maximise flexibility of Robot installation
- Minimise cycle time
- Robot based process control
- Robot based sequence control
- Aim for structured work environment
- Unstructured work environment requires use of sensors
- Minimise human involvement in Robot applications
- Technical specifications of Robot must suit application
- Financial justification of application is essential

1.7.1 Robot Die Casting

- Unload die casting machine
- Quench casting in water tank
- Load trim press
- Unload from trim press onto output conveyor
- Lubricate die with spray gun

**Service more than one die depending on cycle time*

1.7.2 Robots in Spot Welding

Welding Sequence

(a) Squeeze – two surfaces held in contact with electrodes
(b) Weld – current turned on and flows through material. Heat generated in vicinity of electrodes
(c) Hold – tips of the gun kept closed long enough for weld to cool (water circulates through electrodes)
(d) Off – machine rested until next operation

**Frequency of supply used as timing source for control system*
**Squeeze – 8 cycles, Weld – 9 cycles, Hold – 1 cycle*

- *Different programs in Robot memory for various body styles*

- *Robots used in 're-spotting', a single computer controls a series of Robots*

- *Planning Robot spot welding line*

(a) Estimate different types of welds/different welding guns
(b) Group together welds by gun type
(c) Assign a specific group of welds to a particular Robot

- *Estimate Cycle Time*

**Generalised motions in robot weld cycles*

(i) Moving from at rest position to proximity of first weld
(ii) After positioning at work area, adjusting gun attitude to be normal to metal surface
(iii) Performing group of sequential welds in which distance between welds is small and no significant change in the attitude of gun is required
(iv) After performing a group of evenly spaced welds, shifting or skipping along the metal to a second group of evenly spaced welds
(v) Withdrawing gun from metal, removing it completely from work in order to move to an entirely different area. And orientating the gun around the new metal area
(vi) After all welds are completed, withdrawing the weld gun to a clear position so that metal can be indexed or transferred from work station

**Standard times are available for (i) – (vi) and time for the welding process is precisely known*

1.7.3 Robots in Spray Painting

- Unhealthy surroundings for human operators
- Continuous path Robots
- Hydraulic drives or flame proof electric drives
- Different programs in controller for different tasks
- Use of sensors to indicate jobs awaiting painting

1.7.4 Robots in Material Handling

(j) *Machine Unloading:* Free standing Robots fitted to process machines to automat a previously manual unload station. Some machines, (injecting, moulding, die casting), are being manufactured with integral programmable handling devices. Free standing Robots can carry out tasks other than work piece removal such as sprue cutting and cleaning

(ii) Machine Loading/Unloading: If a single Robot is used for loading / unloading the end effecter must be capable of handling the work piece before and after processing of the part at the work station. In addition if the load / unload task has to be repeated on several different process stations the problem of programming the Robot is more complex due to program size and cycle time limitations

(iii) Robot Cell Handling: Using the philosophy of group technology machines are grouped into cells to process a family of parts. The task of the Robot within the cell is to deal with loading, unloading, transportation, sequencing, and synchronization

Robots in Material Handling

- Cycle times should be shorter than / equal to manually operated systems
- Cost and reach considerations force designers to seek compact solutions (less space)
- Robots ensure increased and consistent quality which are often associated with increased control of interprocess storage times and consistent presentation of parts at process stations
- Health and safety considerations contribute to the pressure for introduction of automated handling systems, particularly in hostile / unpleasant environments

The Handling Task

- Handling or 'pick and place' consists of gripping of part, transportation to another location and release
- 'Gripping' consists of positioning the end effector in proximity to part and then attaching part to end effector for transportation
- For gripping to be carried out repetitively and reliably it is necessary to have the part at the exact location and orientation every time. If this is not possible external sensing system will have to be integrated with the Robot
- Transportation is usually carried out by actuation of one or several Robot axes. The exact trajectory of the work piece is usually unimportant provided that collisions are avoided and the part is delivered to the next station as quickly as possible. A Robot having a configuration that suits the handling task will not only require less axes to be used but will also be easier and quicker to program
- Finally, at the delivery station the Robot task involves positioning and orientation of part followed by release of gripping action. If insertion is not required this is a simple operation. Gripper design and programming are important for this task.

Robot Characteristics for Handling

- Good payload capacity
- Large work space / Robot size ratio
- Simple point-to-point or fixed sequence control
- Large Robots capable of moving large loads slowly
- Small Robots capable of moving light loads at high speeds

Robot Controlled Machine Cell

*System consists of machine tolls, gauging equipment and material handling equipment (Robots, AGV's, conveyors). Robot controls operation of system and acts as a source of material handling.

The Robot Cycle operates as follows:

- Robot moves to conveyor carrying parts in random order and signals conveyor to start
- When a part is present at the pick up station a signal is received from a device such as a limit switch. The part is identified just prior to grasping
- Robot move to available machine and checks to see that the previous machining cycle is completed and the door to the machine opened. The end of cycle signal would come from the machine controller and the door open signal would come from a limit switch mounted on the door
- Robot moves to machined part and grasps it and identifies part
- Robot removes part from machine and loads raw material into machine. (Double gripper is used to reduce load / unload time)
- Robot arm is retracted from machine and a signal is sent to the machine controller to close door
- Robot signals the machine to start new machining cycle. (The appropriate machining program for the new part should have been previously specified)
- Robot moves machined part to gauging station
- Decision is taken at gauging station whether to accept or reject part
- Robot transfers part to 'accept' or 'reject' bin based on decision at gauging station
- Data is fed back from the gauging station to the machine via the Robot to adjust tool compensation if part has been rejected due to dimensional drift
- Robot moves to conveyor to begin new work cycle

Robot Controlled Machine Cell

- Part machined in cell to be geometrically similar. Dimensions of parts will dictate gripper design, fixture requirements on machine tool, tooling and machine tool / Robot specifications
- Tool breakage problems have to be addressed with sensors carrying out tool life monitoring
- Chip snarling causes problems when gripping parts and measuring part dimensions. Use of correct chip breaking inserts, feeds, speeds and depth of cut is required. Use of adaptive control techniques may be justified

1.7.5 Other Robot Applications

- Palletising
- Deburring
- Arc welding
- Investment casting
- Forging
- Handling glass
- Drilling
- Gluing
- Assembly

2.0 Economic Evaluation of Robotic Installations

Robot Costs

- Initial purchase price
- Cost of tooling
- Installation costs
- Cost of safety system
- Annual operating costs

Robot Savings

- Savings in direct labour costs
- Savings from reduced rejects / inspection costs
- Increased profits from increased output

Discounted Cash Flow Technique (D.C.F.)

Example:

Year	Capital Costs	Annual Savings	Annual Running Costs	Total Cash Inflow
0	150,000			-150,000
1		40,000	6,000	34,000
2		50,000	6,000	44,000
3		60,000	6,000	54,000
4		75,000	6,000	69,000
5		75,000	6,000	69,000

Year	Total Cash Inflow	Discounting Factor (at rate of 15%)	Discounted Cash Flow
0	-150,000	1.00	-150,000
1	34,000	0.87	29,580
2	44,000	0.75	33,000
3	54,000	0.65	35,100
4	69,000	0.57	39,330
5	69,000	0.50	34,500

**This project breaks even after a period of between 4 and 5 years*

3.0 Robot Safety

Summary of causes for Robot related accidents are listed below:

Cause	Percentage
Erroneous Action of Robot in Normal Operation	5.6%
Erroneous Action of Equipment in Normal Operation	5.6%
Carelessness of Humans in Interacting with Robots	11.2%
Erroneous Action by Humans in Teaching / Testing Robots	16.6%
Erroneous Action by Humans During Normal Robot Operations	16.6%
Erroneous Action by Humans During Checking and Repairs	16.6%
Other	11.2%

The following conclusions have been drawn from the various investigations carried out on Robot safety issues:

- Most organizations that use Robots are aware of the dangers involved
- A high percentage of accidents occur when Robots are manually operated
- Accidents arising during automatic operation occur at a rate significantly higher than for other automated machinery
- Of the accidents associated with Robots more than 50% occur due to Robots malfunctioning
- Robots are inherently safe or foolproof in design and manufacture and depend on the working skill of their users to make them safe

There are two approaches to designing safety systems for Robotic installations, they involve use of (a) warning devices and (b) safety devices.

Warning devices perform two basic functions; Clearly define safety zones and alert humans to the Robot's operational status. Feedback devices enable the Robot system to respond to malfunctions or intrusions into the Robot work envelope. A combination of warning and feedback devices is required to maximize safety.

<u>The Robot workcell can be considered to consist of three distinct zones:</u>

Zone 3:
defined as the space outside the work area. Safeguarding devices should be placed so that humans may observe the Robot at work from a safe distance. Issues in relation to material flow should be considered in designing safety systems for *Zone 3*

Zone 2:
Is the operator work zone. The size of this zone will depend on the application. The Robot control panel and peripheral equipment are mounted in this zone. It is desirable that the boundary between *Zone 2* and *Zone 1* be clearly marked on the floor

Zone 1:
Is the Robot's work envelope. The most effective method of safeguarding in this zone is not to allow any humans within the zone. This is not always possible. Therefore a restricted work envelope should be developed using limit switches etc. to establish boundaries which the Robot will not exceed in the event of any unforeseen failure.

Zone 3 safety is often achieved with the use of wire fencing, pressure sensitive mats, photoelectric fences and camera surveillance. *Zone 1* and *Zone 2* safety is much harder to achieve. Safety at this level is normally achieved using sensor based safety systems.

There are four groups of people that need to be safeguarded: operators, programmers, maintenance personnel and bystanders. Each of these categories of people face unique safety hazards. Additionally, different types of industrial robot applications (eg: painting, welding, material handling etc) impose different and special constraints.

Each application should be evaluated in relation to:

(a) type of robot
(b) type of personnel working with and in the vicinity of the robot
(c) type of application

For example, the approach to guarding will be different for an unmanned machine loading application as compared to an arc welding application where the operator works in close proximity to the robot.

Safeguarding Operators: An operator could perform a variety of functions: starting and monitoring an operation, part feeding and maintenance of the robot. The planned method of operation needs to be established prior to installation so that suitable safeguarding devices can be installed. The devices used should be designed to prevent the operator being within the work envelope during robot operation. They should also inhibit robot motion when the operator is within the work envelope. In addition, a procedure should be enforced which necessitates the operator being located in a certain work area during robot operation.

Safeguarding Programmers: The first consideration in safeguarding programmers is to provide suitable training in robot operation and programming. When the robot is in teach mode the following conditions should be satisfied:

(a) the robot should be under the sole control of the programmer within the restricted work envelope.
(b) the robot should operate at slow speeds only
(c) the robot should not respond to any remote interlocks or signals that cause motion
(d) operation of other equipment in the work area should be under the sole control of the programmer if such operation presents a hazard
(e) all robot system emergency stops should remain functional

(f) the programmer should be required to leave the area covering the robot work envelope prior to initiating automated operation

Safeguarding Maintenance Personnel: Many maintenance personnel are already trained in trade (eg mechanic, electrician etc). Safety techniques that apply to these trades generally apply in the maintenance of robots. The following guidelines assist in developing hazard free conditions during robot maintenance.

a. during maintenance operations within the robot work envelope the maintenance worker should have total control of the robot system
b. the robot system should only be reset for automatic operation after the maintenance person leaves the region of the work envelope
c. a procedure should be established to lockout sources of power or control functions where appropriate
d. for certain maintenance operations, a second person may be positioned at the robot control panel. This person should be knowledgeable in relation to potential hazards associated with the robot system

Safeguarding Unauthorised Personnel: The unauthorised person is the most difficult to safeguard because his/her actions are unpredictable. The following guarding systems could be used to prevent injury to unauthorised personnel entering the robot workspace.

Physical Barriers: This is a means of separating persons from the restricted robot workspace. It should be constructed so as to necessitate the use of tools to remove the barrier and gain access to the restricted area.

Interlock Barrier Guard: An interlock barrier guard prevents access to the restricted work area in a similar manner to the physical barrier. The difference is that there is an opening with an interlock gate. Opening the interlock gate creates one of the following conditions: (a) stops the robot by removing power to the drive motors or (b) stops automatic operation of the robot and any other associated equipment that may cause a hazard.

Perimeter Guarding: Perimeter guards are usually railings located to prevent personnel from reaching into the restricted work area. Any entrance into the general work area of the robot (Zone 2) should be restricted and located so that personnel cannot inadvertently enter the restricted zone. The restricted area should be conspicuously identified.

Presence Sensing Devices: Presence sensing devices are designed, constructed and installed to create a sensing field around the robot system. They detect intrusions into the robot workspace by personnel, robots or other objects. As with the interlock barrier guards, interruption of the sensing field should either (a) stop the robot by removing power from the drive motors or (b) stop automatic operation of the robot and associated equipment that may cause a hazard. Once presence sensing device has been triggered and has stopped the operation of the robot system, both the removal of the object that triggered the device and the deliberate activation of the robot controller should be required to re-start automatic operation. Examples of presence sensing devices include light curtains, pressure mats, capacitive systems, proximity sensors and vision systems.

Awareness Devices: These are primarily warning devices which inform personnel of potential hazards in the robot system. One of the most common warning devices used is a chain or cord attached to posts placed around the robot workspace. The chain or cord is interlocked to the robot control system so that if it is interfered with robot motion will be halted. Another common warning device is a rotating beacon which is energised whenever drive power is supplied to the robot. Since one of the distinguishing features of an industrial robot when compared to conventional machine tools is its ability to move in free space, the light should be mounted on the moving portion of the robot. When this is not feasible, the beacon should be placed in a conspicuous location and a sign placed near the beacon describing its function. Warning signs should be placed all round the robot installation. An audio alarm could also be installed to alert the operator or bystanders when any of the three safety zones have been violated.

Classification of Robot Safety Systems

Sensor based robot safety systems can be classified in relation to their function and use in safety systems. Two commonly used classifications are: (a) generic (task independent) and (b) mapping (task dependent).

The generic system as the name implies can be used in different robot installations, and for different tasks within an installation with little modification. Most *Zone 1* technology is generic. Generic sensing systems for *Zone 2* and *Zone 3* usually involve the monitoring of distances and velocities and comparing them to some pre-determined thresholds. An example is a sensor that monitors velocities and shuts down the arm if an emergency condition occurs.

The converse of generic systems are task dependent systems which are best implemented using a mapping approach. In mapping a teaching sequence is performed, during which the safety system records information (ie distance, velocities) about the task being performed. During operation, the sensing system compares current information with the stored map information and can signal a shutdown if the deviation is too great.

Generic sensing is attractive because of its generality and absence of teaching. However, certain situations and sensor systems are not suitable for a generic approach. A good example is trying to develop a safety system that will enable picking up of components but prevent injury to humans.

Sensor Technology for Robot Safety

There are four sensor technologies that are particularly suitable for incorporation in robot safety systems. They are:

(a) Ultrasonics
(b) Microwaves
(c) Infrared
(d) Capacitance

Ultrasonics: Ultrasound sensing is based on producing a high frequency (above 20 KHz) sound wave and then measuring the time interval until a reflection is detected back at the source. Thus it is necessary to both produce and detect ultrasound signals. The distance to the reflecting object is linearly related to the time delay by the speed of sound. There are certain problems associated with this method of sensing. These include a relatively narrow detection beam (narrow beams are useful for ranging but not for safety applications) and a relatively low repetition rate (10 to 20 Hz). This second problem is usually addressed by circuit resets which must occur between pulses. Nevertheless this can cause problems with high speed robots which may move 10 cm in one tenth of a second. One solution to this problem is to use multiple sensors with overlapping coverage. A third problem that sometimes occurs is production of false triggers which can be caused by multiple echoes. A possible solution is to use multiple sensors and require multiple triggers before flagging a violation.

Microwaves: Two types of microwave based sensors are available (ie presence sensing, velocity sensing). The microwave presence sensing units use amplitude modulated signals. The velocity sensing units are based on the Doppler principle that states that 'when a wave is reflected from a moving object, the frequency of the reflected wave is increased or decreased by an amount proportional to the object's speed'. The velocity sensing microwave units produce an output pulse train proportional to the Doppler frequency shift. By measuring this frequency shift it is possible to determine the approximate velocities of objects in the sensor's detection area. Microwave sensors can be used in both the generic and mapping modes. In the generic mode, the sensors are used to monitor the robot workspace and flat a violation if a velocity threshold is exceeded. This situation could be caused by an out of control robot or an intruder.

In using microwave sensors in the mapping mode there are three problems to be overcome. They are: (a) microwave sensors do not measure very low velocities accurately. This is due to the fact that the Doppler shift frequency is very low and the pulse train output erratic. This problem can be overcome by disregarding small velocities. (b) microwave sensors measure velocity directly towards or away from the sensor, but not those lateral or tangential to the sensor. Therefore an intruder walking laterally across the sensing area might not be detected. (c) the reflected signal is directly proportional to the area of the reflecting object and inversely proportional to the distance of the object from the sensor. Therefore a human intruder might be masked by the signal reflected from a much larger robot.

Infrared: The infrared sensor works on the principle that all objects emit radiation if their temperature is above absolute zero. Humans emit radiation in a well defined spectral range, so sensors have been developed that are tuned to the correct wavelength. In these devices a change in temperature creates a change in polarization or electric charge. Therefore a temperature change will produce a current as a sensor output. Infrared sensors have a fast response and can act as receivers to all human 'transmitters'. Nevertheless there could be a signal generated if there is a slow but steady rise in room temperature and therefore creating a false trigger. This problem could be overcome by using two sensors. Two similar but oppositely wired devices that produce positive and negative signals respectively when there is a temperature rise will eliminate its effects on the output signal. But, an intruder while in motion will produce either a positive or negative signal depending on direction of entry.

Infrared sensors do not work in the generic mode as the motion of the robot itself produces radiation in the 'human' range which performing its tasks (ie thresholding techniques will not work). In the mapping mode of operation the repeatable performance of the robot can be masked out.

Capacitive: In capacitive sensing the changes in capacitance between the sensor and the ground when an intruder is detected triggers a signal. One of the main problems with capacitive sensing systems is their limited range. The sensing unit consists of a control unit, an antenna as the sensor, coupler and connecting cable. The control unit contains the power, comparative circuitry and relays. The antenna can be constructed from copper, galvanised steel or other conductive materials. The antenna shape is configured for the particular application. It is connected to the control unit with a coaxial cable. The antenna and ground act as two plates of a capacitor. The area of the plates and their dielectric constants have a direct effect on the capacitance. For the antenna to be most effective should be placed in the vicinity of the end effector of the robot.

A number of environmental factors have an effect on the capacitive sensor. For example, a change in humidity or temperature can trigger a false signal in the capacitive sensor due to changes in the dielectic constant of the air and hence the capacitance. Capacitive sensors also tend to drift with time and many hours without motion can cause a false trigger. For a mapping type safety system incorporating capacitive sensors to work, a constant nulling circuit will have to be designed.

Integration of Sensor Units: The individual sensing units described previously are available commercially. These commercial units are suitable for operation in the 'generic' threshold alarm mode for intrusion detection. More comprehensive safety systems are best developed by integrating different sensing systems (sensor fusion) under the control of a central microcomputer. Such an approach leads to the following advantages:

(a) Allows more sophisticated processing of signals than simple threshold detection
(b) Can combine information from several sensors prior to making a decision to shutdown the robot system
(c) Filtering of false triggers is more easily carried out within a microscomputer system
(d) Allows tailoring to the particular application

Control System for Robot Safety

The control software for the robot safety system should consist of four modules as follows:

- System configuration mode
- Generic mode
- Teach mode
- Run mode

In system configuration mode the user tailors the sensor system for a particular application by selecting the sensors to be used and initialising control parameters for each sensor system. This mode is also used to display stored data tables for mapped sensors. In generic mode only sensors which are selected for generic operation are activated. This mode is appropriate when teaching of new tasks is carried out using the robot teach pendant. As part of the teaching process new data is collected for the mapped sensors. This function is handled by the teach mode software. Finally, the run mode activates both generic and mapped sensors to achieve a complete safety system.

Requirements of Safety System: Any acceptable robot safety system should have the following characteristics:

- Inexpensive
- Fail safe
- Reliable
- Immune to False Triggers
- Non-fragile
- Able to work in industrial environments
- Immune to power spikes
- Easy to install
- Difficult to by-pass
- Easy to program

4.0 Robot Work Cell Design

In a typical work cell, the robot controller accommodates motion control, sequence control, digital input/output and teach programming.

A programmable logic controller (PLC) would be used to implement control functions in relation to peripheral devices operating independently of the robot.

Identifying independent, simultaneous control activities is the first step in selecting a computer system necessary to control the operation of a work cell.

At the stage of conceptual design of the work cell control system each activity is defined by a functional description and a list of commands and messages which pass across its boundary.

The primary activities which interface with the robot control function and with each other function are safety, operator control and sequence control. These activities provide information about events outside the work cell including operator commands and presence of objects and/or people in the work area of the cell.

The safety and operator control systems continuously monitor all safety sensors, operator control inputs and combinations of conditions in the outside world. The operator control system may respond differently during various phases of operation. For example, manual positioning capability may be locked out during automatic operation of the cell. It is essential that the operator control system always responds in the same way to emergency stop conditions.

Closely related to the functions described above is the sequencing of the overall cell, since operator commands and safety conditions may change the sequence of operations. The robot controller receives the commands for this activity which cause selected robot motions to begin. For example, with a robot that changes tools to do various jobs, the task may be to select an appropriate tool, carry out a cutting operation and replace the tool. The robot controller will respond when the task or a crucial phase of the task has been completed so that sequence controls can continue other operations in the cell.

There are other tasks that may be carried out in the cell which are associated with independent sensing systems. For example, if the robot controller is not capable of sensor analysis and control then a separate vision analysis system, for example, may be required. This system working in conjunction with the robot controller under the control of the sequence controller may be used to identify features of parts in the work area. Information may be passed to the robot about the position of a part of result of part inspection. This information is then passed to the sequence control system to provide a change in sequence based on information from the environment.

A fault and status monitoring system will be used to continuously monitor all operations in the cell and verify motions and conditions. Activities carried out by the fault monitoring system include verifying that a robot arm is retracted from a machine it is loading or that each sequential step on a special purpose device is completed before the next step can begin. If any activity that is incorrect or unsafe has occurred during the sequencing of operations, a message should be sent to a safety and operator control system which should in turn trigger a shut down procedure.

Once the independent functions that are carried out in a work cell are identified and defined the question of which control technology should be used to implement these functions should be addressed. This decision will be based primarily on the number and complexity of independent activities and the sophistication of the robot controller.

In selecting computer equipment, it is important to consider what interfacing techniques will be used between different pieces of equipment. The advantage of combining multiple activities in one computer is that the number of electrical interfaces is reduced. It is desirable to use standard interfacing techniques. For complex sensors, interfaces are usually specific to a manufacturer's product. Frequently, interfacing a robot to say, a vision system, requires special purpose development of an interface.

4.1 Robot Ergonomics: Optimizing Robot Work

The following guidelines should be adhered to in the design of robot tasks:

Reduce Robot Structural Complexity: The number of joints required for the task should be minimised. The number of robot and effector orientations and the dimensions of the robot itself should be minimised. The robot dimensions required for the task would be determined by the distance to be reached by the robot. The payload of the robot requires minimisation as well. The above actions will result in a less expensive robot being required for the task. Other benefits include low energy consumption, simpler maintenance and a smaller work space being required.

Simplify Necessary Motion Path: Point-to-Point motion requires simpler control of positioning and velocity compared to continuous path motion. Therefore whenever possible, point-to-point motion should be specified.

Minimise Number of Sensors Required: Each sensor adds to installation and operating costs due to requirements for additional hardware, information processing and maintenance. Use of local feedback (ie aligning pins) instead of sensors is preferred as no wiring or processing by a control system is required.

4.2 Robot Workplace Design

The layout of a workplace determines, in general, four main work characteristics:

- The distance of movements and motions that must be carried out to fulfil the task
- The amount of storage space
- The delays caused by interference with various components operating in the workplace
- The attitude of human operators working in conjunction with robots

4.2.1 Role of Human Operators in Robotic Systems

Except in totally unmanned operations people will work in co-operation with robots. The roles of humans in robotic systems include the following:

- Surveillance – monitoring of robots
- Intervention – setup, startup, shutdown, programming and maintenance
- Backup – replacing robots during maintenance or periods of breakdown
- Input and Output – manual handling before and after robotic operation
- Supervision – management, planning and exception handling
- Inspection – quality control and assurance other than automatic inspection
- Synergy – combined operations of humans and robots

4.2.2 Robot Work Cycle Analysis

The use of industrial robots raises two overlapping design issues:

(a) Selecting the most suitable robot model and configuration for a specific task
(b) Designing the most effective method for carrying out the task with the selected robot

The above two issues need to be addressed together

The traditional Industrial Engineering approach to Work System Design involves the use of Work Study techniques. A modified version of these techniques termed 'Robot Time and Motion' (MTM) has been developed for robot based work cell design. RTM is similar to MTM which was developed for human work and is based on standard elements of work.

<u>Robot Work Cycle Analysis</u>

RTM methodology: The RTM methodology involves use of three modules. These are RTM elements, robot performance models and an RTM analyser.

There are ten general work elements defined in the RTM methodology. These ten elements are divided into four groups:

Group 1: Motion elements representing arm movements and re-orientation with or without payload.

Group 2: Sensing elements which represent sensory actions by robots that are equipped with position, force or vision inputs.

Group 3: Gripper or tool elements that depend on the type of robot end effector.

Group 4: Delay elements that add specific time durations according to processing and waiting requirement.

Each element is specified with certain parameters, such as distance moved, angle of rotation etc. Each type of robot will have its own parameters.

Element Tables: The simplest modelling approach which follows the original MTM approach for human work methods, applies a set of tables with estimates for each element according to particular parameters. Tables are developed based on laboratory experiments with the robot type for which data is required. The advantage of this approach is its simplicity. Once tables are developed for a variety of robot types, the user can retrieve the time estimates for a task method evaluation either manually or using a computer aid such as the RTM system. In practice it has been found that the deviation of predicted time from actual time was within 5%.

Regression Equations: This modelling approach is considered useful when observation values are random or when a complicated functional relationship has to be approximated. Both conditions apply in the case of robot work. Robots are very consistent in their operation but experiments have shown that robot performance varies with dynamic changes in electric power or hydraulic pressure. Regression techniques developed for the RTM system have shown to yield an accuracy within 5%.

Motion Control: While the previous two modelling approaches have traditionally been applied in time and motion studies the motion control method can be used when knowledge about the engineering design of a robot is available. Models of motion control are mainly useful for the Group 1 elements specified in the RTM method. These models can also be applied for gripper motions that belong to Group 3.

A typical motion control is applied according to pre-designed patterns of the robot velocity. Once such pattern combines three main sequences of motion velocity: acceleration, motion at user specified velocity and deceleration.

For example, in the case of a 5 axis electrically driven robot with a 5 Kg payload the total motion time is found using the formula:

$$S / V + 1 / 4 \text{ for } S > V / 4$$

where S is the total distance moved and V the user specified velocity. It is assumed that the robot starts from a stationary position and moves to a stop. In certain short motions, the robot does not have sufficient time to reach the user specified velocity. In the ideal case this happens whenever $S < V / 4$.

In practice several other factors including overhead for computing, minimum time to prevent shocks, jerks etc have to be considered.

As a result the model described above has to be modified to

$$T = S / V + 0.365$$

When $S > V / 2.857$

$$T = 0.413 \text{ for } S < 6.25 \text{ cm}$$

$$T = 0.610 \text{ for } 6.25 < S < 17.5 \text{ cm}$$

$T = 0.8$ for $17.5 < S < 43.75$ cm

Where
T - total motion time
S - total distance moved
V - user specified velocity

Other factors that should be considered when using the MTM method for cycle time analysis are limitations to motions that involve excessive rotation and combined rotation and linear motion. The accuracy of the Motion Control method has been determined to be within 3%.

Path Geometry: Robot motions can also be modelled by specifying the motion path geometry. Based on robot joint and link velocities the motion time can be computed. The linear and rotational distances to be travelled by each join in relation to the previous joint can be calculated when it is specified that the end effector has to move to a specific location. The time it takes to complete the motion will depend on the longest individual link or joint motion time. Path geometry computation programs have been implemented within the RTM methodology for certain types of robots. The accuracy of this method is about 12%.

5.0 Robotic Assembly

5.1 Components of System

1. Automated Work Stations
   (a) storage devices for holding components
   (b) orientation and feeding mechanisms for presenting components to work head
2. Manual Assembly Stations
3. Transfer System for Transporting Partially Completed Assemblies from Work Station to Work Station

5.1.1 Component Features

1. Consistent shape and size
2. Free from burrs and flashing
3. Require minimum amount of orientation
4. Have sufficient features for easy orientation
5. Free from oil and swarf
6. Smooth surface finish
7. Ability to withstand high speed mechanical handling damage

5.2 Design of Machines for Automated Assembly

Factors to be considered:

- Process
- Accuracy of placement
- Plant layout
- Operator ergonomics
- Access for Maintenance
- Required production rates
- Safety aspects

5.3 Types of Assembly Operations

1. Press fitting
2. Welding
3. Riveting
4. Screwing
5. Bonding
6. Stitching

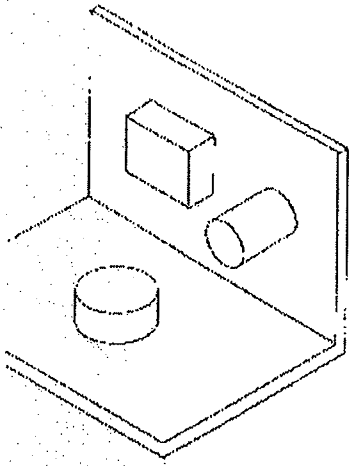
5.4 Product Design for Automation

- Base or main body which will serve as its own fixture
- Locating surfaces or holes for fixturing
- Simple straight line vertical loading motions
- A minimum of multiple or compound motions
- Adequate bearing surfaces to maintain assembled relationships

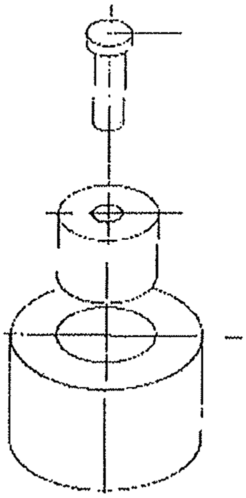
- Part strength for high speed assembly forces
- Burrs, flashes in directions which will assist assembly

5.5 Design Rules

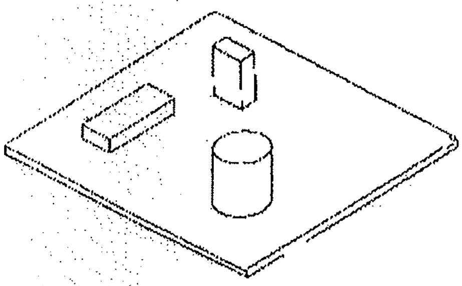
A. Method of Construction
   1. Frame Construction
   2. Stacked Construction
   3. Base Component Construction
   4. Modular Construction



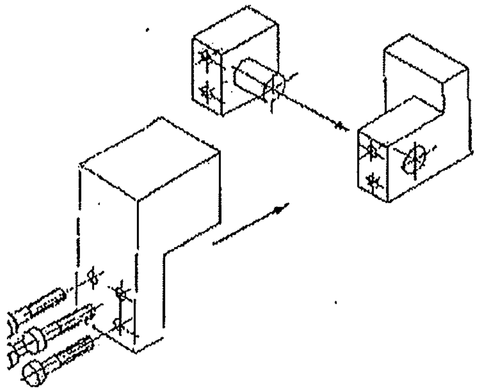
Frame Construction



Stacked Construction



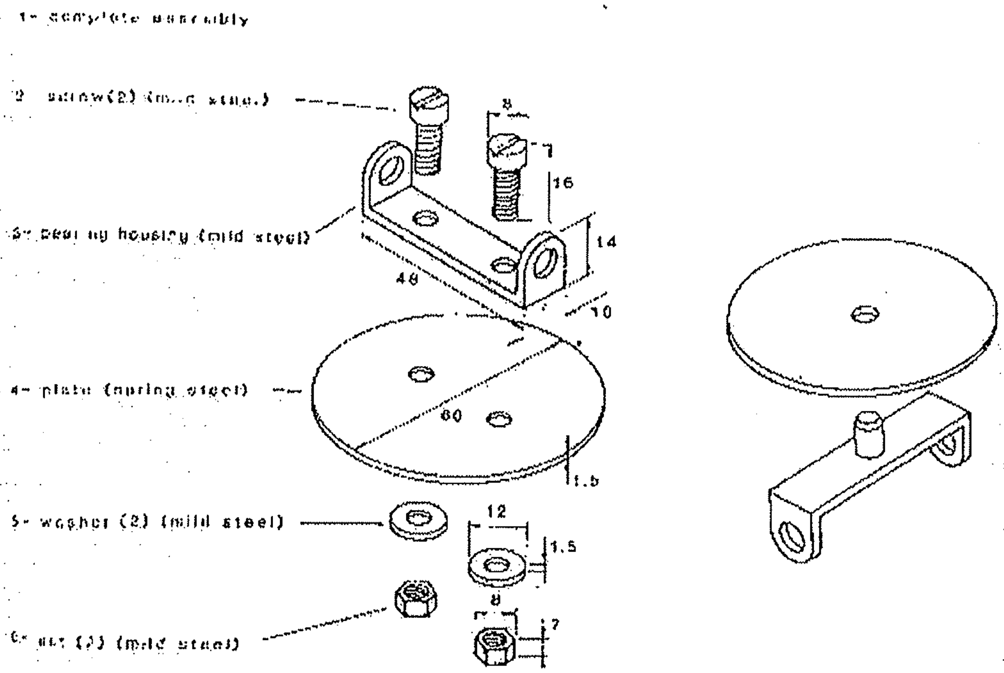
Base Component
Construction



Modular Construction

5.6 Design of Components for Assembly

- Check whether every item in an assembly is necessary
- Use precedence diagram to check sequence of assembly
- Ensure that each component is fully and correctly specified
- Minimise component variation
- Use symmetrical components if possible
- If a part is to be asymmetric exaggerate it
- Design product/component for uni-directional assembly
- Maximise functions performed by each component in the assembly (minimise components)
- Product should be designed to suit machine work ethic and not human methodology
- Orientation of a sub-assembly must remain known and preferably constant throughout the assembly sequence
- When a sub-assembly is moved it should be structurally sound or protected by a jig
- A sub-assembly should not be committed to a particular product until it is as far up the assembly chain as possible
- Components and sub-assemblies must be handled without damage



Diaphragm Assembly

(dimensions in mm)

Re-Design for Assembly

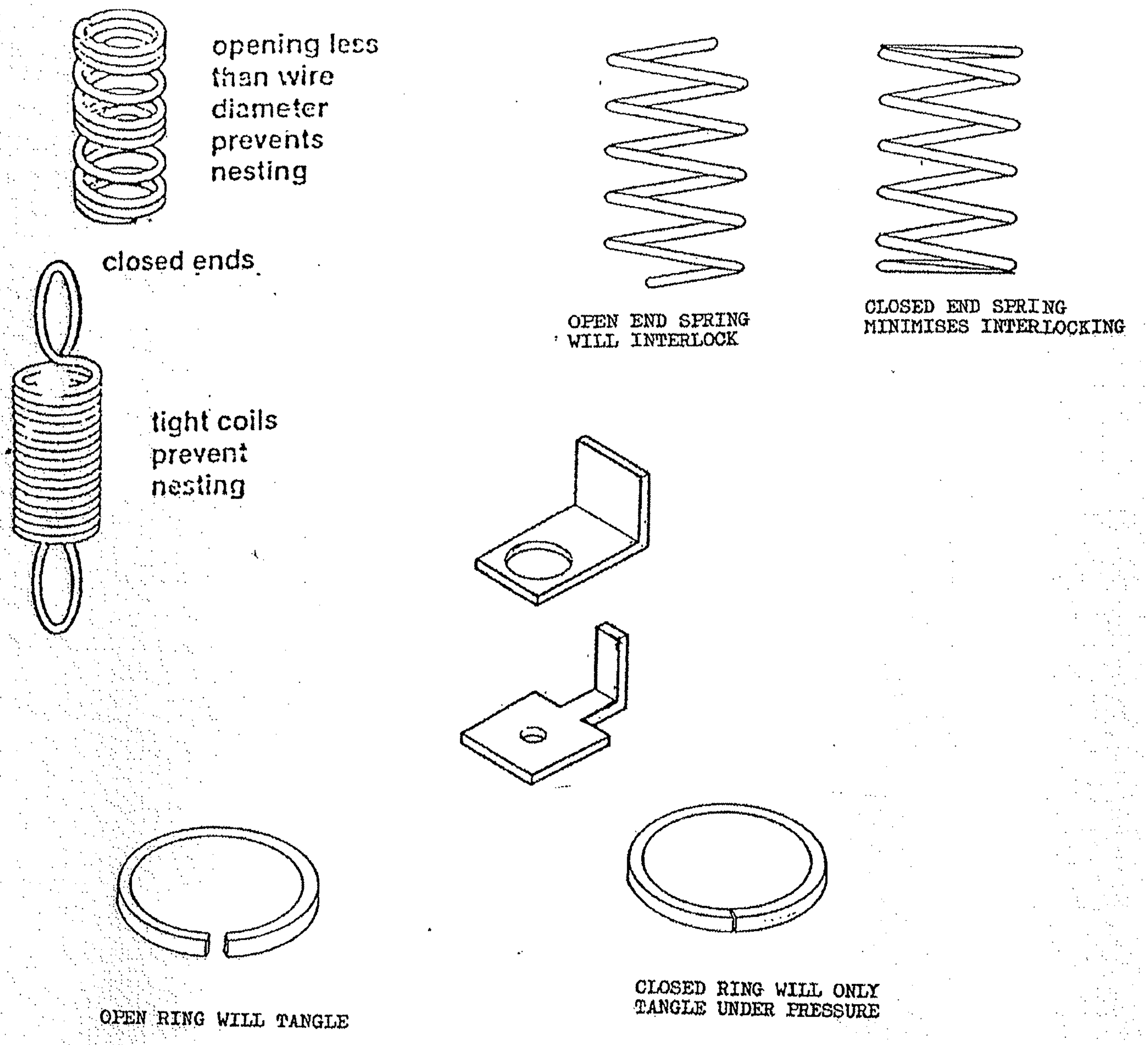
5.7 Analysis of Assembly Tasks

- Position
- Grip
- Pick
- Move
- Place
- Fit
- Feedback

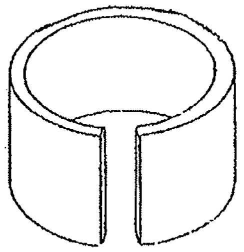
5.8 Factors Affecting Automated Assembly

A. Tolerances
B. Design of components, sub-assemblies, products
C. Automated Feeding

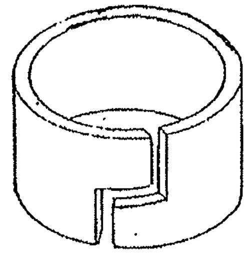
Problems associated with:
Tangling
Nesting
Telescoping
Shingling
Orientation



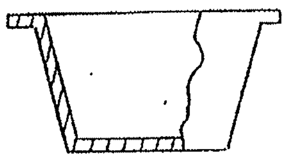
Design for Automated Feeding



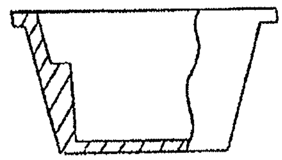
STRAIGHT SLOT WILL TANGLE



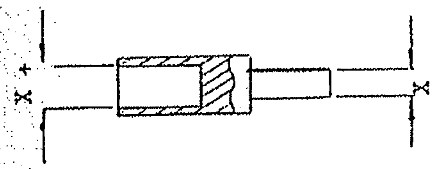
CRANKED SLOT WILL MINIMISE TANGLING



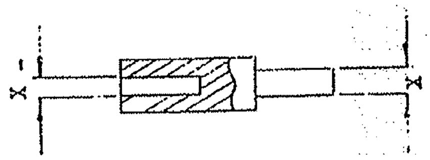
POSSIBILITY OF NESTING



NESTING WILL NOT OCCUR

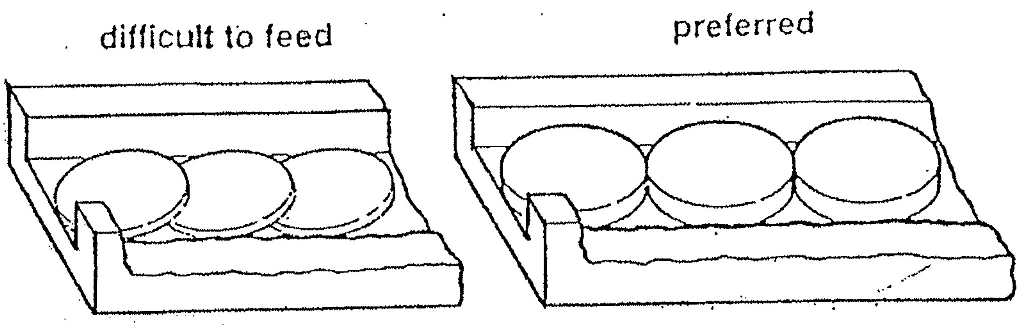


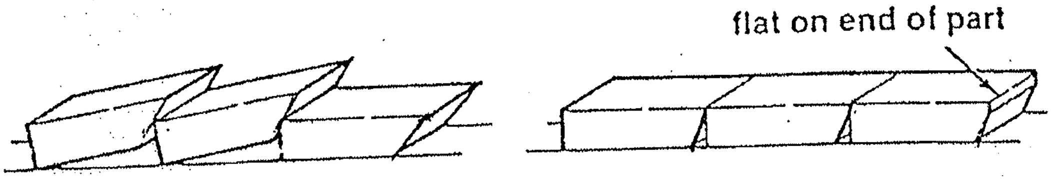
POSSIBLE TELESCOPING OF COMPONENTS



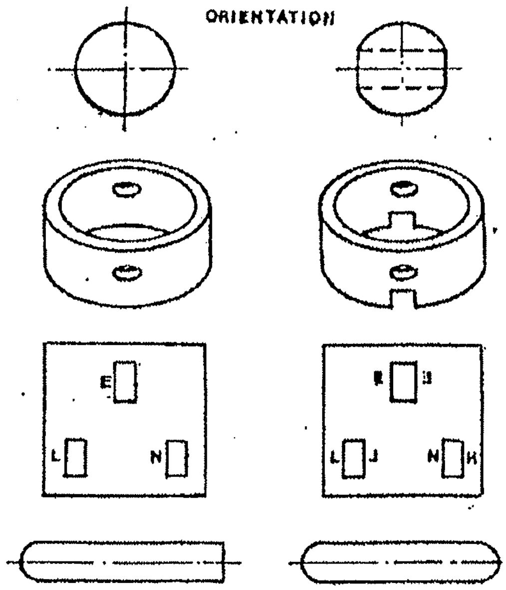
END TO END FEEDING POSSIBLE

Design for Automated Feeding





Avoid parts which shingle



Design for Automated Feeding

5·9 AUTOMATED ASSEMBLY

DESIGN OF COMPONENTS FOR ASSEMBLY

- CHECK WHETHER EVERY ITEM IN AN ASSEMBLY IS NECESSARY
- USE PRECEDENCE DIAGRAM TO CHECK SEQUENCE OF ASSEMBLY
- ENSURE THAT EACH COMPONENT IS FULLY AND CORRECTLY SPECIFIED
- MINIMISE COMPONENT VARIATION
- USE SYMMETRICAL COMPONENTS IF POSSIBLE
- IF A PART IS TO BE ASYMMETRIC EXAGGERATE IT
- DESIGN PRODUCT / COMPONENTS FOR UNI-DIRECTIONAL ASSEMBLY
- MAXIMISE FUNCTIONS PERFORMED BY EACH COMPONENT IN THE ASSEMBLY (MINIMISE COMPONENTS)
- PRODUCT SHOULD BE DESIGNED TO SUIT MACHINE WORK ETHIC AND NOT HUMAN METHODOLOGY
- ORIENTATION OF A SUB-ASSEMBLY MUST REMAIN KNOWN AND PREFERABLY CONSTANT THROUGHOUT THE ASSEMBLY SEQUENCE
- WHEN A SUB-ASSEMBLY IS MOVED IT SHOULD BE STRUCTURALLY SOUND OR PROTECTED BY A JIG
- A SUB-ASSEMBLY SHOULD NOT BE COMMITTED TO A PARTICULAR PRODUCT UNTIL IT IS AS FAR UP THE ASSEMBLY CHAIN AS POSSIBLE
- COMPONENTS AND SUB-ASSEMBLIES MUST BE HANDLED WITHOUT DAMAGE

DESIGN FOR ROBOTIC ASSEMBLY

- **Ensure that parts that are not secured immediately on insertion are self locating in an assembly.**
- **Holding down of unsecured parts cannot be carried out by a single robot arm, therefore special fixturing is required which must be activated by the robot controller. This adds significantly to special purpose tooling, and hence, assembly costs.**
- **Design parts so they can be all gripped and inserted by the same gripper. One major cause of inefficiency with robot assembly systems arises from the need for gripper or tool changes.**
- **Even with rapid gripper or tool change systems, each change to a special gripper and then back to a standard gripper is approximately equal to two assembly operations.**
- **The use of screw fasteners always results in the need for tool changes since robot wrists can seldom rotate more than one revolution.**
- **Design products for assembly in layer fashion from directly above. This ensures that the simplest, least costly and most reliable four degrees of freedom robot arm can accomplish the assembly tasks. It also simplifies the design of the special purpose work fixture.**
- **Avoid the need for re-orienting a partial assembly or manipulating previously assembled parts. These operations increase the cycle time without adding value to the assembly.**
- **If a partial assembly has to be turned to a different resting aspect during the assembly process, this will result in increased work fixture costs and the need to use a more expensive six degrees of freedom robot arm.**

- **Design parts that can be easily handled in bulk. To achieve this avoid parts which tangle, nest, are flexible or have thin / tapered edges which can overlap when moving along a conveyor or feedtrack.**

- **Avoid parts that are delicate or fragile to the extent that re-circulation in a feeder would cause damage and those that are sticky or magnetic so that a force comparable to the weight of the part is required for separation.**

- **Avoid parts that abrasive and wear the surfaces of automated handling systems and light parts which can cause conveying problems due to air resistance.**

- **If parts are to be presented using automatic feeders, then ensure that they can be oriented using simple tooling. Feeding and orienting at high speed is seldom necessary in robotic assembly.**

- **In robotic assembly the main concern is that the features which define part orientation can be easily detected.**

- **If parts are to be presented using automated feeders, then ensure that they can be delivered in an orientation from which they can be gripped and inserted without any manipulation.**

- **Avoid situations where a part can only be fed in one orientation from which it must be turned over for insertion. This will require a six degrees of freedom robot and special gripper or a special 180 degrees turn delivery track.**

- **If parts are to be presented in magazines or part trays, then ensure they have a stable resting aspect from which they can be gripped and inserted without any manipulation by a robot.**

COMPONENT DESIGN FOR ROBOTIC ASSEMBLY

- IF POSSIBLE, HAVE PARTS JOINED OR CONNNECTED WITHOUT USING FASTENERS BY HAVING THEM DESIGNED SO THAT THEY MAY BE SNAPPED OR INTERLOCKED TOGETHER
- IF THE USE OF FASTENERS CANNOT BE AVOIDED, USE FASTENERS THAT CAN BE FED AUTOMATICALLY. FASTENERS WITH A LENGTH TO DIAMETER RATIO OF AT LEAST 1.5 : 1 ARE MOST EASILY FED
- IF A WASHER IS REQUIRED, HAVE IT CAPTURED BYA SCREW OR BOLT. IT SHOULD NOT BE A FREE PART.
- USE THE SAME FASTENER THROUGHOUT THE ENTIRE ASSEMBLY. AVOID USING DIFFERENT SIZES AND TYPES OF FASTENERS
- FASTENERS ORIENTED VERTICALLY ARE THE MOST ACCESSIBLE TO AUTOMATED EQUIPMENT
- ALWAYS ALLOW ADEQUATE CLEARANCE AROUND THE FASTENER FOR AN AUTOMATED TOOL
- USE FASTENERS WITH FLAT SIDES AND TOPS SO THEY MAY BE EASILY PICKED UP USING VACUUM OR MAGNETIC DEVICES

COMPONENT DESIGN FOR ROBOTIC ASSEMBLY

- A FLEXIBLE PART IS MORE DIFFICULT THAN A RIGID PART TO ASSEMBLE BECAUSE THE POSITION OF THE PART IS VARIABLE
- PARTS TO BE ASSEMBLED BY ROBOT SHOULD BE RIGID AND STIFF
- MOST DIFFICULT FLEXIBLE PARTS FOR ROBOTIC ASSEMBLY ARE BELTS, WIRES AND CABLES
- PARTS SHOULD BE DESIGNED TO BE COMPATIBLE WITH GRIPPING
- PARTS WITH LARGE, FLAT AND SMOOTH TOP SURFACES ARE BEST FOR VACUUM OR MAGNETIC PICK UP
- IF PARTS CANNOT BE HANDLED USING VACUUM OR MAGNETIC GRIPPERS THEY SHOULD HAVE APPROPRIATE HOLES, SLOTS OR TABS TO AID IN GRASPING
- PARTS SHOULD FIT TOGETHER ONLY ONE WAY AND NOT REQUIRE A SECONDARY OPERATION FOR ALIGNMENT. GUIDEPINS, D – SHAPED HOLES AND NOTCHED SLOTS ARE EXAMPLES OF WAYS THAT PARTS CAN BE ASSEMBLED IN ONLY ONE CONFIGURATION
- PARTS CAN BE SELF ALIGNED USING HOLES, CUTOUTS OR TROUGHS DESIGNED TO SECURE A PART IN A PARTICULAR ORIENTATION
- PARTS CAN BE MADE TO FIT TOGETHER EVEN WHEN THEY ARE MISALIGNED BY USING CHAMFERS AND LEAD-INS.
- PARTS WITH HIDDEN FEATURES SUCH AS HOLES, SLOTS, PINS ETC THAT MUST BE ORIENTED WITH RESPECT TO THESE FEATURES SHOULD HAVE CORRESPONDING EXTERNAL FEATURES TO ASSIST IN ORIENTING THE PART

Product Design Rules for Ease of Feeding

- Keep tracking surfaces flat and large
- Keep the centre of gravity low
- Minimise the number of orientations required
- Keep profiles distinctly different
- Avoid designs which nest, tangle, shingle, jam or wedge
- Keep parts stiff and rigid
- Design flash, burrs into areas least likely to interfere with assembly

5.10 Parts Feeding in Automated Assembly

Feeding mechanisms are classified as:

- Feeders
- Orientation devices
- Feed tracks
- Escapement devices
- Magazines

FEEDERS: Feeders accept parts in random orientations, store them temporarily and activate them so that they can be subjected to the action of the orientation devices. Parts are transferred from the feeder to the work head by means of a feed track which is designed to maintain parts in the correct orientation. As most part feeders cannot supply parts at the precise rate of assembly they are usually adjusted to over feed slightly and escapement devices are used to 'meter out' parts as required.

Vibratory Bowl Feeder: The vibratory bowl feeder is the most versatile of all hopper feeding devices, for small engineering parts. In this type of feeder the track along which the parts travel is helical and passes around the inside wall of a shallow cylindrical hopper or bowl. The bowl is usually supported on three or four sets of inclined leaf springs secured to a heavy base.

Vibration is applied to the bowl from an electromagnet mounted on the base. The support system constraints the movement of the bowl so that it has a torsional vibration about its vertical axis, coupled with a linear vertical vibration. The motion is such that any small portion of the inclined track vibrates along a short, approximately straight path. This path is inclined to the horizontal at an angle greater than that of the track. When component parts are placed in the bowl, the effect of the vibratory motion causes them to climb up the track to the outlet at the top of the bowl.

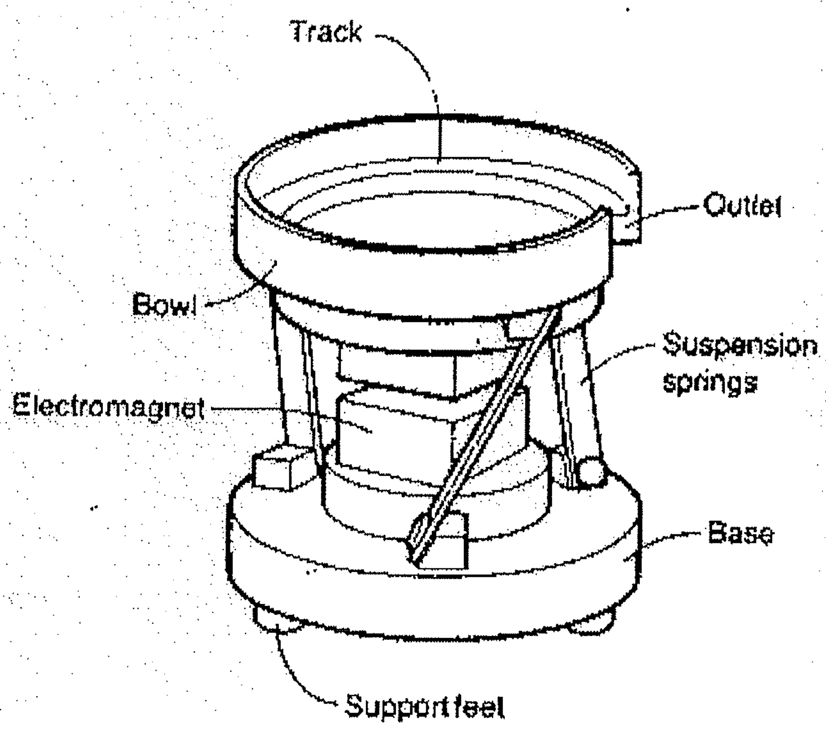
One of the main disadvantages of vibratory bowl feeders is their change in performance as the bowl gradually empties. This change occurs because for a constant power input, the amplitude of vibration and hence the maximum bowl acceleration usually increases as the effective mass of the loaded bowl reduces. This increase in bowl acceleration will generally increase the unrestricted feed rate. The change in performance as a bowl gradually empties is referred to as its load sensitivity. One of the simplest solutions to load sensitivity is the use of a load detector switch together with a secondary feeder. The load detector switch is a mechanical arm and limit switch that detects when the level of parts in the bottom of the bowl falls below some pre-determined level. When this pre-determined level is reached the switch activates the secondary feeder and re-fills the bowl to a pre-determined level. This action essentially increases the frequency of re-fills, reducing the re-circulation effect to almost zero.

Vibratory bowl feeders are often used to convey and orient parts for automatic assembly. Since the work heads on assembly machines are designed to work at a fixed cycle time the parts can only leave the feeder at a uniform rate. The feeder must therefore be adjusted to over feed slightly under all conditions of loading. Excess parts are continuously returned from the track to the bottom of the bowl.

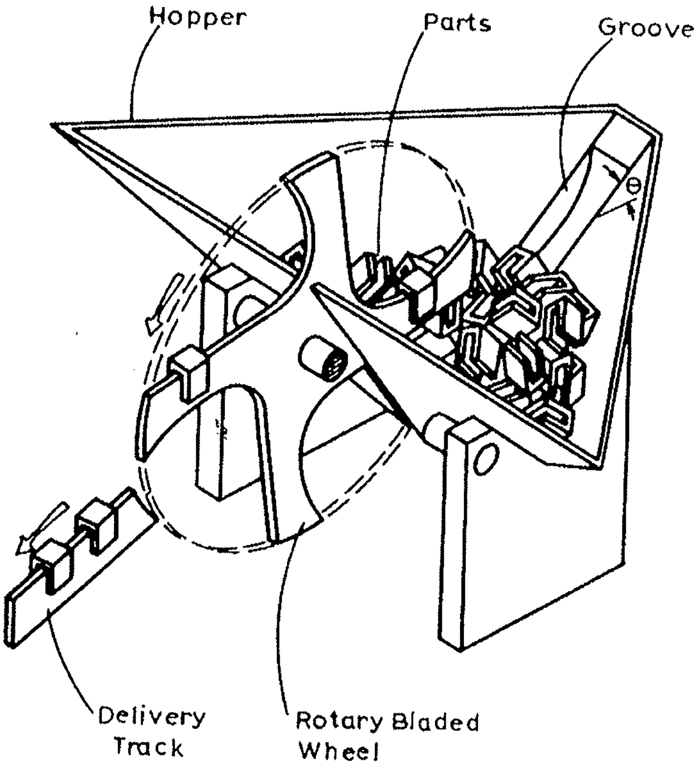
Limitations to performance of conventional vibratory bowl feeders include:

(a) since the velocity of parts up inclined tracks is always less than that of parts travelling around the flat bowl base, parts jam in the various selecting and orienting devices fitted to the bowl track.
(b) conveying velocity of parts is very sensitive to changes in the coefficient of friction between part and track (ie low velocity at low friction)
(c) at high feed rates there is an increase in the amplitude of the normal component of vibration and this may cause erratic hopping and bouncing of parts.

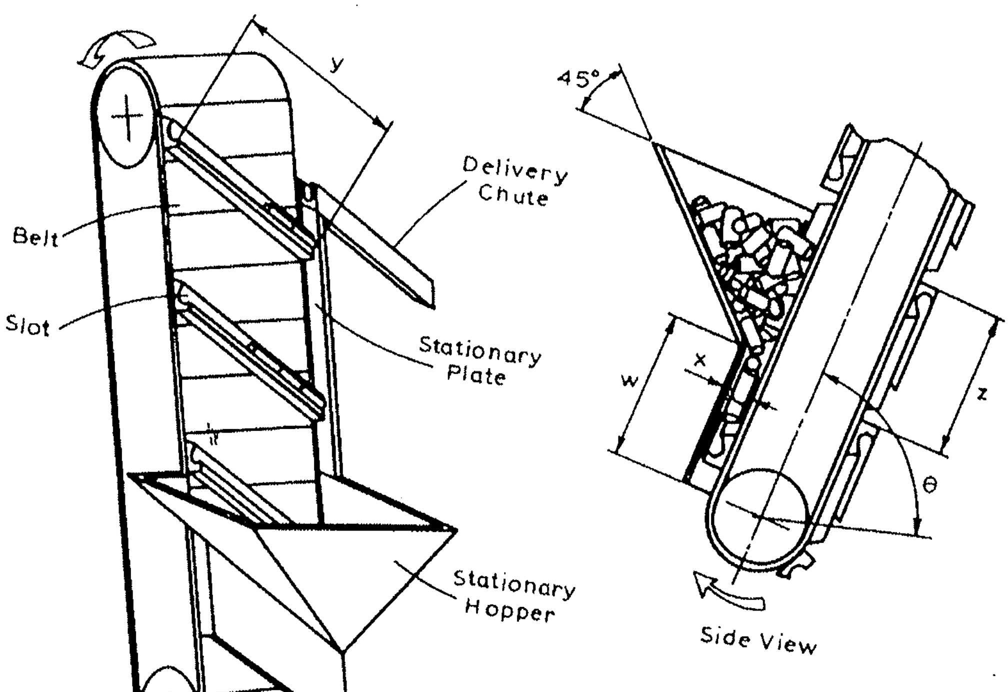
There are other types of feeders such as reciprocating feeders, rotary feeders and belt feeders that are also used in automated assembly operations.



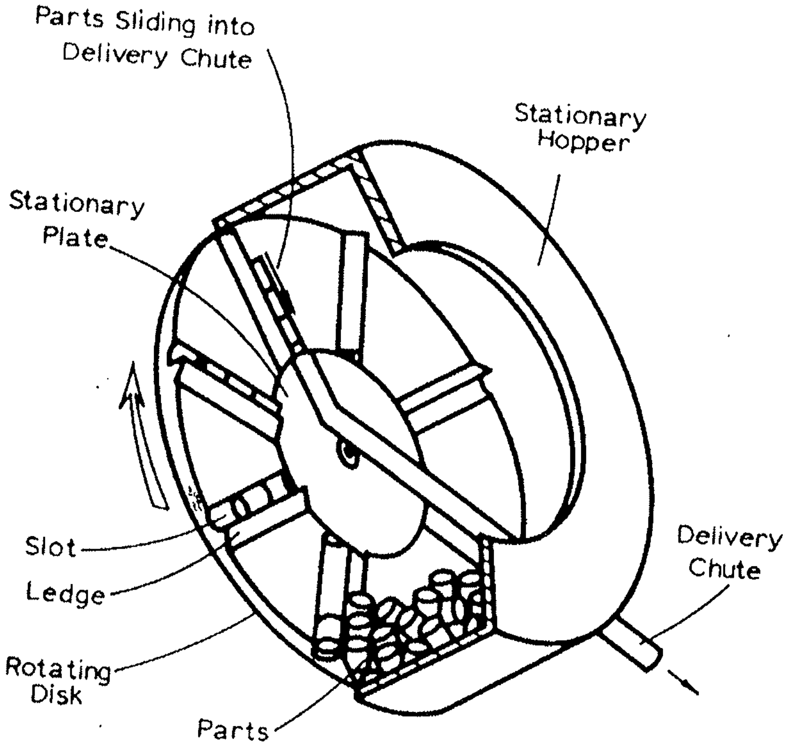
Vibratory Bowl Feeder



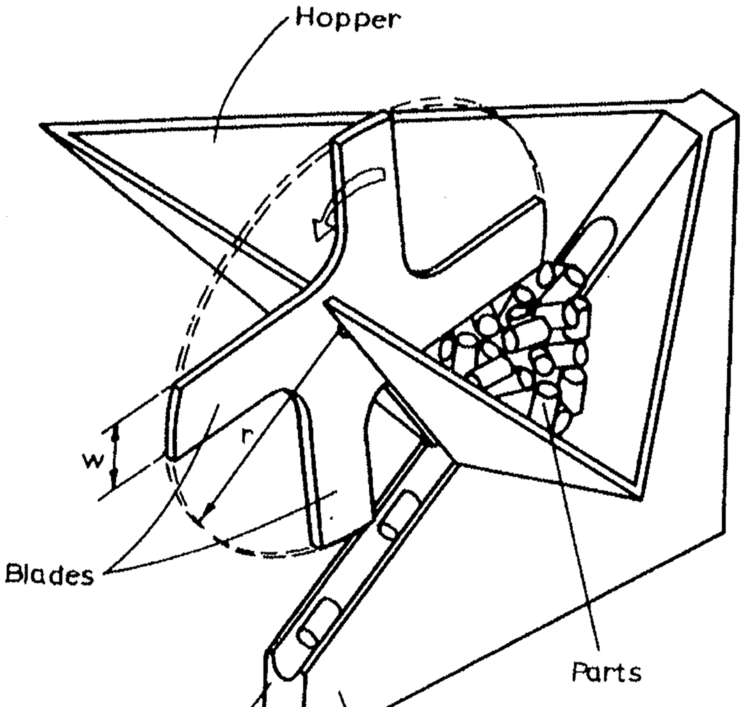
Rotary centerboard hopper.



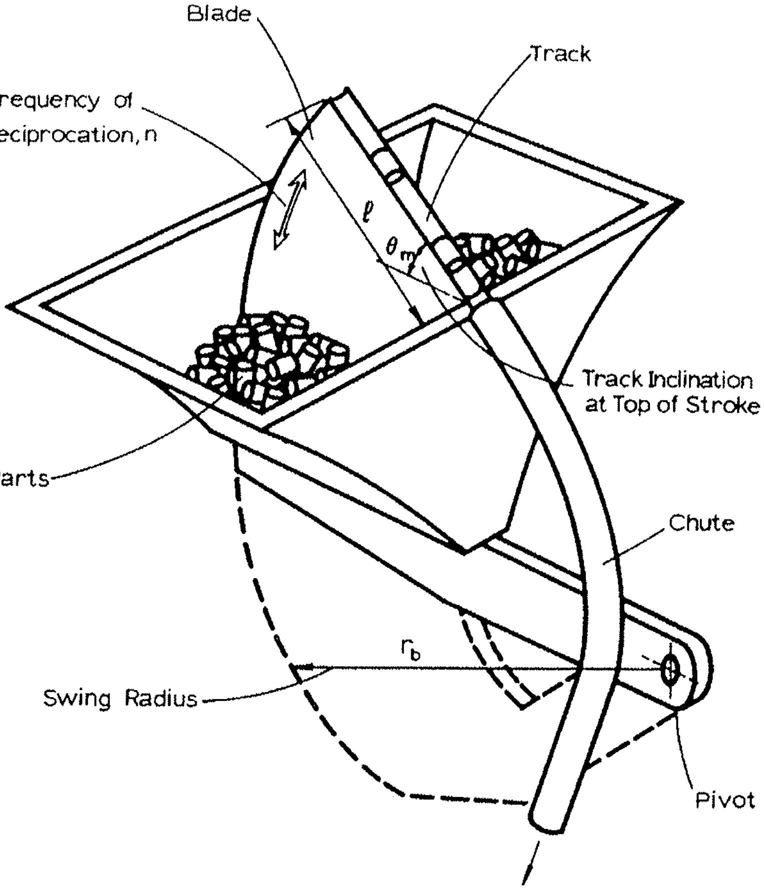
Elevating hopper feeder.



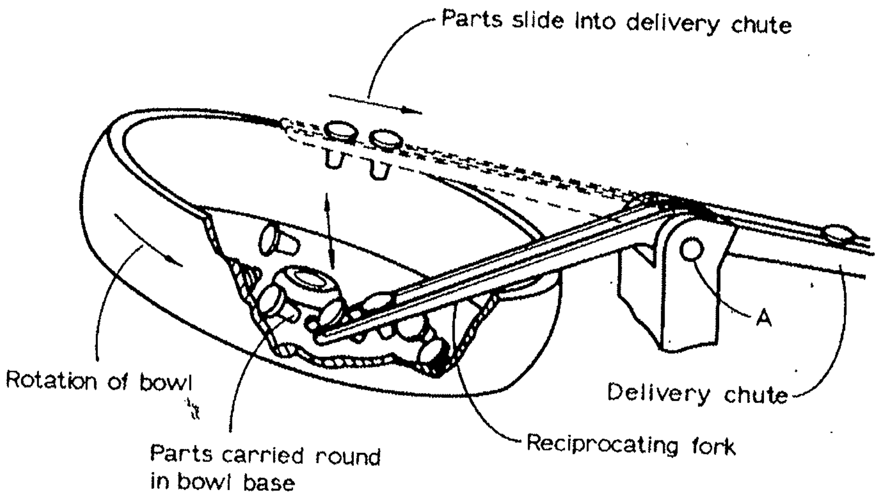
Rotary-disk feeder.



Bladed-wheel hopper.



Centerboard hopper feeder.



Reciprocating-fork hopper.

One of the most popular approaches to enhancing feeder flexibility is to use sensor based feeders which restrict the function of feeders mainly to parts storage and presentation while leaving recognition of parts to a sensory system and subsequent orientation to a robot or auxilliary system.

Optical sensors have been used along the vibrating track of a bowl feeder to replace mechanical orientation devices. A camera mounted directly above a translucent polycarbonate block which is set flush into the vibratory track is used to view parts. Backlighting is often used in this configuration to illuminate the parts.

Laser detection systems has been used in combination with bowl feeders to enhance feeder flexibility. Parts are fed through a laser diagnostic zone where scattered light intensities are generated, measured and compared with a re-set signature. The system is capable of identifying a range of components with slight asymmetrical features too small to be recognised by mechanical devices.

Current state of the technology in terms of sensory systems dictates that feeders developed for general purpose assembly should be retained for storage, conveying, orientation and presentation of parts in flexible assembly systems. This is done by extending the capability of conventional part feeders by incorporating adjustment and/or interchangeability into their dependent components (ie orientation devices).

Programmable feeders have been developed for (i) small thin parts (ii) rotational block parts among others. They incorporate sensors in additional to programmable diverting blades and orientation devices driven by motors with feedback systems and controlled by computers.

ORIENTATION DEVICES: Orientation devices can either by incorporated in the parts feeder or fitted to the feed track between the feeder and the work head. Most orientation devices are passive, working on the principle of orientation by rejection of all incorrectly oriented parts. Active devices designed to re-orient parts are sometimes used with out of feeder tooling arrangements.

Orientation devices used for vibratory bowl feeders have been categorised using a two digit coding system. The first digit represents the basic device configuration (flat, sloping track) while the second digit distinguishes the various device modifications (rail, slot, gap). The coding system is a guide for designing an orientation device for a particular situation.

Frequently more than one orientation device is necessary to manipulate a part to a desired orientation. These devices collectively form an orientation system whose overall efficiency is the ratio of number of properly oriented parts delivered by system to the number of parts entering it.

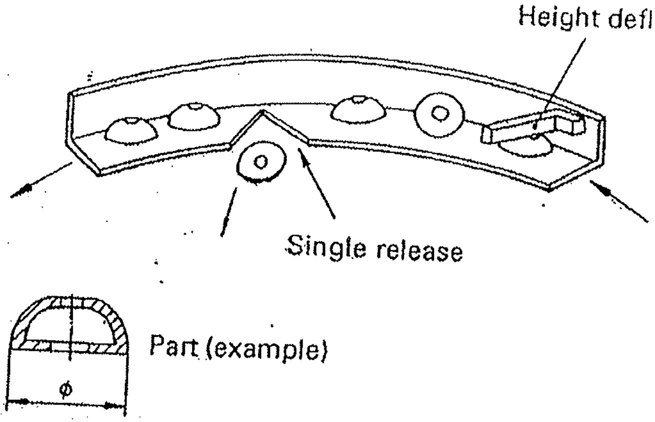
With different combinations of orientation devices more than one orientation system is often available for transforming a heap of randomly scattered parts to various specific orientations. Although it is desirable to select a system which will turn out parts with the required attitude in mechanised assembly the choice is usually influenced by the orientation systems part delivery rate because of the need to match it with the high rate of the assembly machine.

FEED TRACKS: In order to provide easy access to automatic work heads and assembly machines part feeders are usually placed some distance away from the work head. This means that the parts have to be transferred and maintained in their oriented position between the feeder and the work head by means of a feed track.

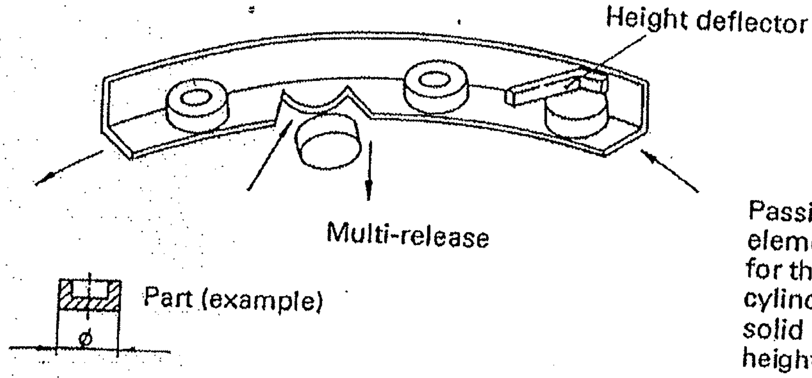
Feed tracks are classified as either gravity tracks or powered tracks. Gravity tracks are simple but their feeding performance depends greatly on the slope of the track, frictional resistance between contact materials and if entry into work head is horizontal, number of components held in track.

ESCAPEMENT DEVICES : In automated assembly the output of parts from a feeder is always restricted by the machine/equipment it is feeding. The machine will use parts at an uniform rate which is usually lower than the unrestricted feed rate of the feeder. Excess parts delivered by the feeder may be stored or re-circulated. Nevertheless at times the feeder has to be stopped on detection of a full track. As most feeders do not supply parts at the discrete intervals required by the work head, a metering device (Escapement Device) is necessary to ensure that parts arrive at the automatic work head at the correct time. Although an escapement can be activated by the movement of the work carrier it is usually activated by some work head mechanism (ratchet mechanism, slide escapement).

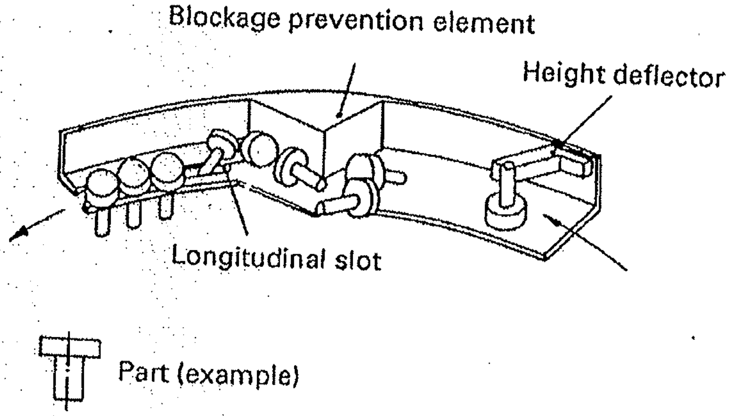
MAGAZINES: Another way of delivering parts to an assembly machine is to load them into a container/magazine which constrains their orientation. The magazine is attached to the work head and parts are fed by spring action or gravity. The loading of the magazine is done by human labour.



Passive arrangement element: by a single release for the arrangement of taper or pyramid parts in combination with a height deflector.

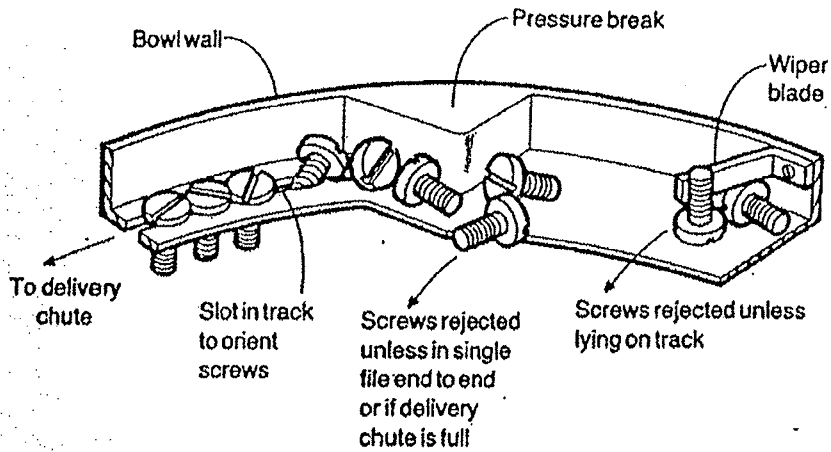


Passive arrangement element: by a multi-release for the arrangement of cylindrical parts – one end solid combined with a height deflector.

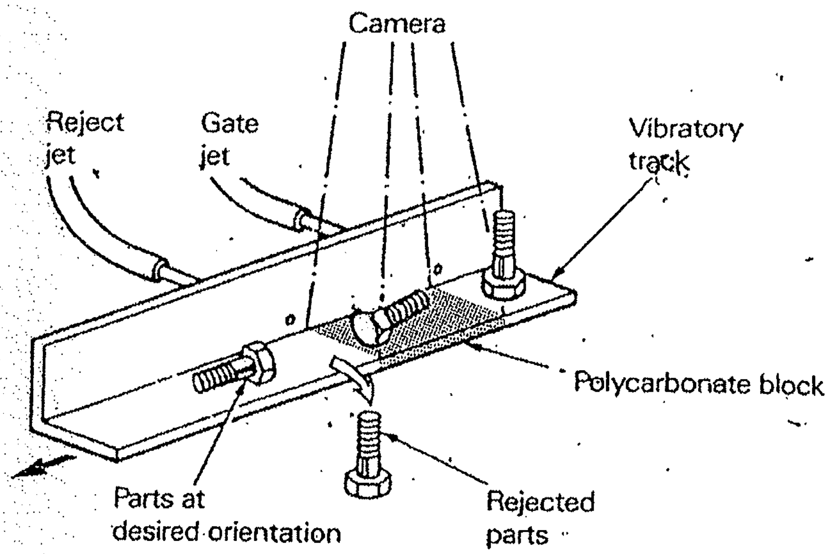


Passive arrangement element: by a longitudinal slot for the arrangement of mushroom-head parts (suspended) in combination with a height deflector and a component to prevent blockages.

Part Orientation for Automated Assembly



Orientation of screws in a vibratory bowl feeder



Part Orientation for Automated Assembly

5.11 Basic Systems Concepts for Automated Assembly

Single Station Concept: This consists of a single station to which are brought two or more parts of the assembly to be joined. A number of different operations may be performed providing the tooling does not get excessively complicated or difficult to maintain.

Synchronous Dial Concept: This consists of a circular fixture plate which contains multiple fixtures or nests uniformly placed around the periphery. The plate rotates a fraction of one turn at pre-determined time intervals progressively presenting each fixture to a number of stations.

The number of fixtures/stations is dependent on the number of operations required. The indexing cycle time may be controlled through some uniform timing device or all stations must complete their functions prior to indexing of the plate.

This concept offers many advantages including use of minimal floor space, minimum number of fixtures, high speed operations and a high level of standardisation among available bases and tooling components.

Limitations of this concept include physical size, torque required to index fixtures and space available for part loading and auxilliary devices such as hopper feeders.

Speeds of upto 3600 parts/hour can be achieved. Parts of upto 50 cm in diameter can be accommodated and between 6 – 10 operations are common.

Synchronous In-Line Concept: A series of fixtures or holding devices attached to chain or steel belts are moved from one work station to the next in straight line motion. All fixtures are moved at the same time and over the same distance resulting in all fixtures sequentially passing all stations in a straight line. Indexing intervals may be controlled by timers or on a 'demand type' basis indexing only when all stations have completed their individual functions.

In-line indexing machines which are fixtured usually return the fixture on a conveyor based below the assembly area. If the part serves as its own fixture this problem of returning fixtures is overcome.

In-line indexing mechanisms offer more operations than are practical with the dial concept. Disadvantages include accumulated inefficiencies of many stations (ie limited to 15-20 work stations on hopper fed equipment) and the slowest operation pacing the line.

Speeds of upto 1500 assemblies/hour are common with more possible with multiple tooling. Indexing mechanisms include air and hydraulic cylinders, geneva mechanisms and hydrostatic drives.

Synchronous Carousel Concept: This is similar to the synchronous in-line concept but the work is moved in a rectangular path with pallets being returned to their starting point. All parts are indexed at the same time by the same distance using a timer or on a demand basis.

Advantages associated with this concept include utilisation of all the fixtures in the system and efficient use of space.

__Non-Synchronous Concept:__ Individual stations may operate independently and without regard to other operations in the system. Work pieces without fixtures or work pallets are free to move independently being powered by belt chains, motors or other power sources. Parts or pallets may be stopped individually at any point for manual or automatic work. They may also accumulate or 'back up' at these stations to allow for variations in station work time.

The advantages of this concept include the possibility of single tooling the faster operations while multiple tooling the slower operations with as many stations as necessary on the same machine base. Another advantage is that the accumulating characteristics of the independent pallet travel permits the 'averaging out' of the variations in manual operations without penalising the automatic operations. The third advantage of this concept lies in the virtually unlimited number of operations which can be tied together, subject only to mechanical limitations such as drive torque. Perhaps the most important advantage of this concept is the capability of adding manual standby stations after many (or all) of the automatic stations for use during a breakdown.

Many non-synchronous systems are completely modular. The basic work transfer mechanisms are standard and independent of operation stations.

The disadvantages of this concept include cost, as several fixtures are required for each work station to take advantage of the accumulation characteristics (line variances, down time etc).

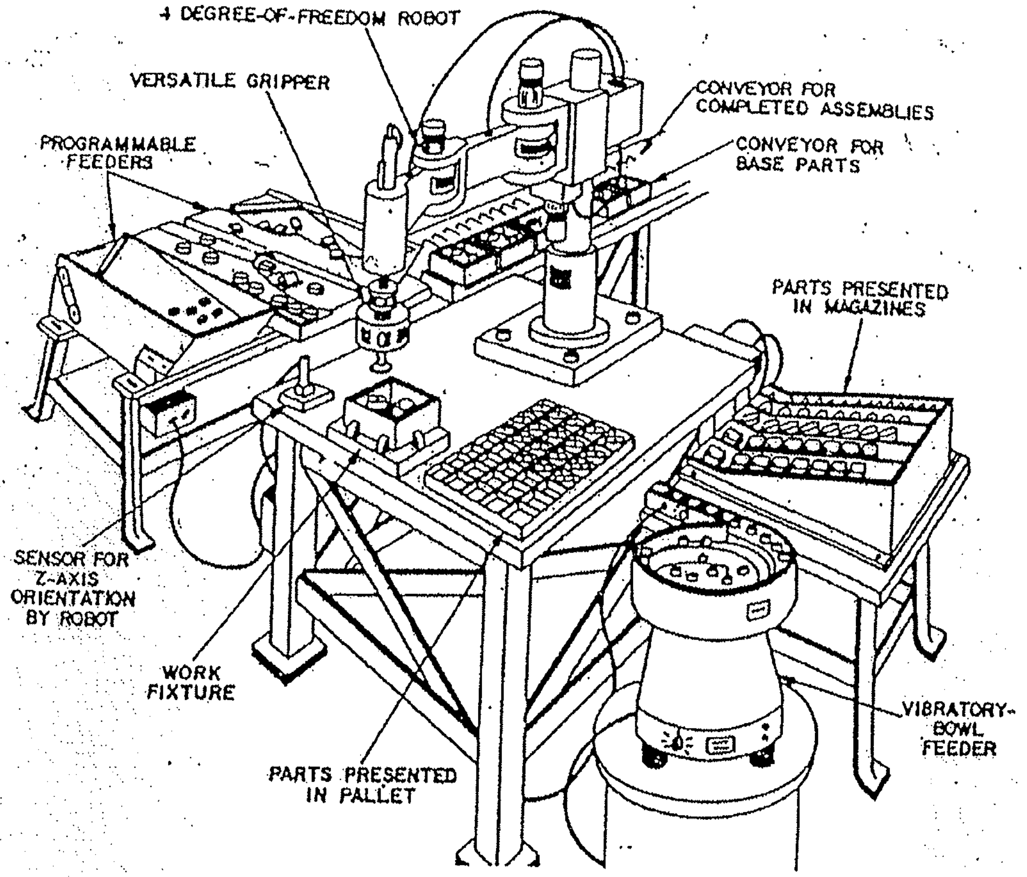
Production rates are usually less than for synchronous systems (600-900 parts / hour).

Inline non synchronous systems offer the 'in one end out the other' work flow advantage with the associated disadvantage of space requirements. There is also the disadvantage of having to return pallets to the starting point.

Carousel configurations bring the work back to the starting point with concurrent material handling problems. Nevertheless this configuration requires less floor space.

__Continuous Systems Concept:__ This concept involves work pieces and fixtures being attached to a conveyor system which operations continuously. Any work performed whether manual or automatic is done 'on the fly' by stations or operators who move with the work pieces while performing a function. These systems are the most widely used, primarily for manual assembly operations.

This concept is the most costly of those discussed.



Basic single-station one-arm assembly system

5.12 Basic Systems Concepts

Selection of a basic system concept is the most important step in the process of automating an assembly operation.

Factors that determine the selection of a concept for the design of an assembly system include:

- Production rate
- Physical size and weight of components/product
- Manual operations involved
- Number of automated operations
- Complexity of operations
- Material handling and supply logistics
- Line balance of operations
- Controls
- Repair and offline operation

Factors in System Concept Selection

Production Rate: A production rate of 750 assemblies per hour can be obtained from any of the system concepts described. Physical size, complexity of operations, number of operations etc will determine the most suitable system for any specific application.

A single station concept is recommended for production rates of upto 1000 assemblies/hour provided the number of operations are limited.

The synchronous concept is suitable for production rates of upto 3600 assemblies/hour. The number of operations and their complexity as well as the proportion of manual to machine labour will determine whether the in-line or carousel concept is suitable.

Non-synchronous systems are usually limited to production rates of under 1000 assemblies/hour.

Continuous systems are suitable for low production rates and larger assemblies (eg engines).

Physical Size and Weight: In selecting a system concept the accuracy of positioning and equipment required for assembly as well as work transfer should be considered.

Very small assemblies frequently pose the problem of the required precision location. Single station machines offer the easiest solution where there are few operations. Synchronous and non-synchronous concepts should be considered in turn as the number of operations and degree of manual assembly increase.

Manual Operations Involved: Where production rates, product design and economics are compatible it is always desirable to eliminate manual operations completely. Where this is not possible consideration must be given to the number of manual operations required and their complexity.

For a single station concept manual operations may be confined to loading and unloading of components.

On a synchronous machine a number of manual operations may be involved. The dial concept permits one or two, the in-line concept offers space for a number of operators, and the carousel offers still greater opportunity for mixing people and automation.

The non-synchronous concept offers a special inducement for the mixture of manual operations with automation in that the variations in manual operating time from part to part may be averaged out for a minimum effort of operator pacing of automatic operations. Furthermore, the non-synchronous concept will permit several operators to perform the same function while the rest of the line which is automated operates with single stations.

The continuous systems concept has been associated with manual operations for large assemblies and automated operations for small assemblies particularly at high production rates.

Number of Automated Operations: The single station concept is limited in space and accessibility to a very few automated operations.

The synchronous dial concept also has a distinct space and accessibility limitation. Fewer operations may be possible due to station inefficiencies. As the number of automated operations goes up the required efficiency per station acquires critical proportions. Individual station efficiency must be very high (high 90's) to permit more than six stations to be coupled together. A number of techniques have been devised to increase the efficiency of synchronous systems. These include auditing and repair loops.

However, accumulating inefficiencies and the fact that the breakdown of one station shuts the entire system limit the number of automated operations in one synchronous system.

The continuous system concept has the same general limitations as the synchronous concept as all stations are effectively coupled together with little chance of recovering lose production.

In theory non-synchronous systems can handle both automated stations and breakdowns of automated equipment better than other systems with their 'averaging out' effect. This is the result of a more effective mix of manual and automated operations.

Complexity of Operations: This factor is a highly individual one depending on the parts being assembled and the functions which must be performed. Complexity like the number of automated operations involved must be carefully weighed against the efficiency of the various concepts on an individual basis.

Line Balance of Operations: All single station, synchronous and continuous systems effectively couple together all operations at a speed of the slowest operation involved. This can be occasionally avoided on a synchronous system by having two or more identical operations working on alternate parts. Other than this possibility, non-synchronous systems offer the greatest opportunity to accommodate a balanced line.

Tooling Concept: The selection of a system concept will depend to some extent on the tooling concept. Whether the part must be fixtured or whether it can serve as its own fixture will have to be considered whatever system concept is selected. Fixtures are expensive and have to be maintained. They should be eliminated through product design if possible.

Single station, synchronous systems in the main have all work stations coupled together. Non-synchronous systems permit the use of completely self-contained, independent work stations which may be removed, replaced or re-tooled without affecting the system operations. Multiple tooling and fixturing are possible on all systems.

Material Handling: Space and equipment requirements for material handling are sometimes greater than that required for assembly itself. A typical synchronous type assembly system involving a dozen hopper fed components of fairly large size may use upto four times as much space for material handling and storage as compared to the assembly operation itself.

Synchronous and non-synchronous in-line equipment offers the opportunity to spread out auxilliary units (for handling) to permit more orderly handling of material and accessibility for operators and maintenance personnel.

Continuous systems will consume incoming material at an even greater rate and should be carefully engineered to ensure that log jams do not occur.

6.0 ROBOT END EFFECTORS

Robots are essentially computer controlled machines that can be directed to move to specified locations with a great deal of accuracy. In some robots the path taken between programmed locations can also be precisely defined. Nevertheless no useful work is done by a robot at these pre-defined locations. The actual task is carried out by a tool or gripper attached to the robot end plate. Therefore it is extremely important to design or select the appropriate end effector for a specific task.

Robot end effectors are of two types:

a) Tools

b) Grippers

Commonly used robot tools are :

a) Spot welding guns

b) Arc welding torches

c) Spray painting nozzles and containers

d) Rotating spindles for drilling, routing etc.

e) Heating torches

f) Water jet cutting equipment

In using the above tools with robots it is only necessary to carry out minor modifications if any to the equipment that is used by human operators. The major task is to design the interface between robot and tool to ensure that the tool is securely fixed to the robot end plate and that power (electric, pneumatic etc) can be transmitted through the robot system to the tool without in any way obstructing operations. Some thought needs to be given to designing the interface so that the tool can be quickly attached to and detached from the robot end plate preferably without human intervention. It is also necessary to ensure that the tool is always attached to the robot in the same orientation. Failure to do this will result in having to re-program the system each time a tool change is made.

Robot grippers (also referred to as end effectors) are usually of four types :

a) Mechanical grippers

b) Vacuum grippers

c) Magnetic grippers

d) Adhesive grippers

1 Mechanical Grippers

There are two methods of constraining a component in a mechanical gripper.
One method involves physically constraining the components within fingers attached to the gripper. The more common method involves gripping the component between two fingers which form an integral part of the gripper. The method is discussed further in the following paragraphs.

Figure 1.1 illustrates the working of a typical mechanical gripper

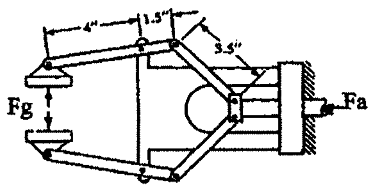


Figure 1.1 : Mechanical Gripper

One of the primary objectives of the gripper design is to minimise the force 'Fa' required (usually produced by compressed air) to achieve a value for 'Fg' that will be sufficient to grip and transport the workpiece (component) at the required speed. This is usually accomplished by varying the lengths of the links (figure 4.1). One of the constraints attached to this method is that there are limits to the travel allowable for the gripping surfaces. The limits will be dependent on the range of dimensions of the components to be handled and space constraints relating to the workspace / work cycle.

A simple empirical formula is used to calculate the gripping force "Fg" for transportation of a component of mass 'M'.

$$Mf*n*Fg = M*g$$

where

Mf - coefficient of friction of contact surfaces against component

n - number of contact surfaces (usually two)

Fg - gripping force

M - mass of component being transported

g - gravity

If the robot is accelerating during the work cycle a safety factor is used in the calculation of the gripping force 'Fg'. This safety factor 'S' = 3, when the robot is accelerating in the direction of gravity forces; 'S' = 2, when the acceleration is in a horizontal direction and 'S' = 1 when the robot accelerates in a direction opposing gravity.

As can be deduced by examining the formula listed above, the gripping force 'Fg' can be reduced by increasing the frictional coefficient between the component and the gripping surfaces. This is achieved in practice by using polyurethane bonded steel pads on the contact surfaces. The main body of the gripper is made of aluminium to reduce the weight of the gripper.

The issues discussed previously in relation to designing the interface between various tools and the robot end plate are equally valid in the design of the interface between the robot and the gripper.

There are instances where more than one gripper has been attached to the robot to reduce the cycle time of the task. Typically two grippes have been used in applications where robots are used for material handling in a manufacturing cell. Up to ten grippers have been attached to robots used for complex assembly operations.
Space and 'payload' constraints limit the number of grippers that can be attached to an individual robot.

6.2 Vacuum Grippers

Vacuum grippers are used in situations where the components to be transported have a small mass and only one surface is available for gripping. Vacuum type grippers are effective only if the surfaces to be gripped are smooth, flat and clean. Vacuum can be produced by a vacuum pump or a venturi device. Use of a vacuum pump is the more expensive option but it enables the gripping and transportation of a larger mass than the venturi device. Venturi devices are cheap but noisy.

In addition to enabling gripping and transportation of a component using only one of its surfaces vacuum type grippers have the following advantages :

a) Applying uniform pressure across the whole surface

b) Enable the use of relatively light weight grippers

c) Are applicable to a variety of materials

A major disadvantage of vacuum grippers is that they cannot handle components with holes.

The area / number of suction pads required to grip and transport a specific component is calculated using the following simple formula :

$$F * S = P * A$$

where

F - force or lift capacity (equal to weight to be transported)

S - safety factor (1.3 – 2.0)

P - vacuum or negative pressure available (based on capability of vacuum device)

A - total effective area of suction cups

Vacuum sensors should always be used in conjunction with vacuum grippers to ensure that sufficient negative pressure (vacuum) is available when components are to be gripped and transported.

6.3 Magnetic Grippers

Magnetic grippers obviously can handle only metallic components. Nevertheless there are distinct advantages associated with this type of gripper. Advantages are :

a) Pick up times are very fast

b) Can handle various shapes of components

c) Can handle components with holes (unlike vacuum grippers)

d) Requires only one surface for gripping (as with vacuum grippers)

The are some disadvantages associated with magnetic type grippers :

a) Residual magnetism in the component handled by the gripper can be a problem in subsequent handling

b) Not very precise in that more than one component may be picked up (eg: more than one metallic sheet)

Electromagnetic type grippers powered by direct current (D.C.) improve the ability to control the degree of magnetism (hence solve problem (b) listed above) and also enable a more effective release of components at the end of the handling cycle.

Permanent magnet type grippers although cheaper in that no external power source is required necessitate the use of a stripping device to detach components from the gripper at the end of the handling cycle.

6.4 Adhesive Grippers

Adhesive grippers have been designed to handle 'soft' materials such as textiles. An adhesive substance applied / attached to the gripper performs the gripping action. As with vacuum and magnetic type grippers adhesive grippers require only one surface for gripping. The disadvantages associated with adhesive grippers are :

a) Reliability of the gripper reduces with usage and the adhesive part of the gripper has to be replaced / replenished at regular intervals

b) A stripping device is required to detach components from the gripper at the end of the handling cycle.

5.5 Gripper Design Exercise

A gripper mechanism is to be designed for a robot that is required to transport fire bricks from the outlet of a furnace to a group of pallets. The robot is also required to stack the firebricks in appropriate pallets according to a pre-determined stacking pattern. There are three sizes of fire bricks produced and their dimensions are as follows:

350 mm x 220 mm x 100 mm

350 mm x 200 mm x 100 mm

350 mm x 180 mm x 100 mm

The density of fire bricks is 200 Kg / cubic metre.

The fire bricks are stacked in three separate pallets depending on their dimensions. A sensor system is used to determine the size of each fire brick as it reaches the exit point from the furnace. The appropriate robot program is then selected to place the brick in the selected pallet according to a pre-determined stacking pattern. The major constraint in placing the fire bricks in the pallets is that a gap of 3mm should separate one fire brick from another.

The robot selected fro this application is of a cylindrical configuration. The robot specifications are as follows :

Payload	3 Kg
Repeatability	0.5 mm
Maximum Speed	0.5 metres / sec
Maximum Acceleration	0.5 metres / sec

It is a requirement that the speed and acceleration characteristics of the robot should be exploited to the full in order to minimise the cycle time of the material handling task.

It may be assumed that the fire bricks exit the furnace area individually and are cooled to room temperature prior to their reaching the exit location. The design of the exit from the furnace enables each fire brick to be located precisely and in a single orientation prior to handling. The fire brick surface is smooth, dry, clean and for all practical purposes non porous on exit from the furnace.

Hint : the most suitable design would be a gripper mechanism that combines two separate grippers, one mechanical and the other of the vacuum type. The 'hybrid' gripper would enable the two objectives, namely, minimising cycle time and maintaining a gap of 3 mm between fire bricks to be achieved. The major challenge would be to design a gripper mechanism as described above which also satisfies the payload constraint.

6.6 Tools and End Effectors

The following tools have been used as robot end effectors :

- Spot Welding Guns
- Arc Welding Torches
- Spray Painting Nozzles
- Rotating Spindles for (a) drilling (b) routing (c) grinding (d) wire brushing
- Heating Torches
- Water Jet Cutting Tools

6.7 Robot End Effector Interface

The interface between the end effector and the robot arm has to accommodate the following functions :

- Power supply to end effector (pneumatic, electric, hydraulic, mechanical)
- Control signals to actuate the end effector (pneumatic, electric, hydraulic, mechanical)
- Feedback signal transmission to the robot controller (electric)
- Overload protection for the robot (i.e.: shear pin)

6.7.1 Designing Mounting Surfaces for End of Arm Tooling (E.O.A.T.)

The following guidelines should be adhered to in designing mounting surfaces for end of arm tooling (E.O.A.T.).

- Most frequent mounting procedure is bolting
- Include facilities for air, fluidics and electrical signals at E.O.A.T. / Robot interface mounting plate.
- Place emphasis on design of interface between robot and E.O.A.T. so that if necessary robot can change its own tool automatically or position itself so as to provide easy access to maintenance personnel who will change tools manually.
- When a given E.O.A.T. is removed for maintenance / modification there must be a specific mechanism or method for replacing the E.O.A.T. in the same position and orientation it originally had.

6.8 Gripper Design

The following characteristics are important in gripper design :

- Payload
- Inertia
- Centre of Gravity
- Centrifugal Force
- Material Used
- Power Source

- Requirement for Handling Multiple Parts
- Design for Multi-Purpose Operations
- Working Environment
- Maintenance Considerations

6.8.1 Gripping Surfaces

Cylindrical parts can be gripped either on the inside or outside diameters. Both gripping methods are self centrering. When gripping an inside diameter it is a two point contact while gripping outside diameters should be effected with a 'v' block. This provides four point contact.

Cast surfaces are usually used on grippers when surfaces being gripped allow scratching. Otherwise a soft non-marking gripper should be used.

When gripping heavy parts the centre of gravity of the part should be located close to the axis of the grip.

The most popular gripping surface is polyurethane bonded steel. It withstands cyclic loads, has a high coefficient of friction and does not mark. If the gripper has to 'bite' into the part surface hardened steel surfaces with knurls are required.

6.9 Dual Gripper Concept

The following situations call for consideration of installation of dual grippers :

- Minimisation of machine down time
- Servicing machine tools with dual work stations
- Handling part size variation caused by machining processes
- Handling two different sized parts that are processed together
- Requirement for increased production rates

Limitations of dual grippers include :

(a) gripper weight
(b) gripper size

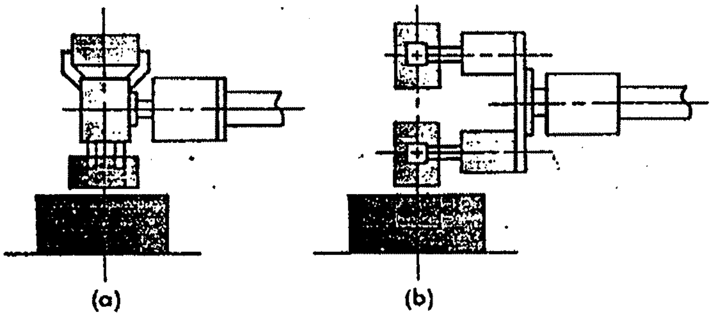


Figure 1.2 : Dual Gripper

6.10 Gripper at Both Arm Ends Concept

The gripper at both arm ends concept provides the following advantages :

- Cost Savings – if a dual gripper is mounted on one end of a robot an additional wrist axis is required. Multi – functional grippers involve larger size and weight. Grippers at both arm ends provide a solution involving less cost and simpler tooling.
- Increased Production – grippers at both arm ends concept provides increased production in comparison to a single handed robot.

6.11 Two Arm Concept

Two separate robots, each with one gripper, can be operated with one controller and one power supply under certain conditions. One of the controllers can be thought of as doing nothing more than controlling additional axes of motion, which in this case are two separate robot arms. The following criteria must be satisfied prior to applying the two arm / one control system concept.

- Layout or cycle time must preclude the use of only one robot
- Application should allow both robots to work simultaneously on process
- Robot controller must have adequate memory and capability to control both arms

6.12 Gripper Exchange Mechanism

Advantages :

- Reduce end effector weight
- Increase flexibility of robot
- Enable simpler, optimal gripper design

Disadvantages :

- Problems associated with connecting different power lines
- Exchange mechanism adds weight to payload
- Design of gripper exchange mechanism is complex