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Information Package

INDUSTRIAL ROBOTS IN SMALL-AND MEDIUM SCALE FACTORIES.

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I.INTRODUCTION

This information package should give a first introduction in problems appearing by application of industrial robots and manipulators especially in small- and medium scale factories. The industry of many smaller -developing and developed- countries is dominated by such factories.

In field of application of industrial robots and manipulators today experiences are available mostly for large scaled factories (e.g.car factories, steel works, factories for the production of electronic devices...) mainly in industrialized countries. A broade. introduction of industrial robots in smaller countries will be more difficult than in larger and more industrialized countries. In addition other criterias and facts have to take into consideration.

Therfore this short information starts with various definitions fo. industrial robots used today. A survey about the different types of commercial available industrial robots yields to an outline about robot applications and application examples. Of great importance are statistical datas for the diffusion of robots into the production in small as well as large- scaled industries. After these more general statements special emphasis will be devoted to small and medium scale factories. Technical, economical and social implications related to the introduction of robots in such factories mainly in developing countries will be discussed. Finally the importance of the introduction in developing countries is underlined and recommandations for an efficient and successful application are given.

1. Robot definition and classification.

Industrial robots as a tool for automatization have been developed for the improvement of the people from recurring, monotonous activities.

Industrial robots form a part of manipulators which might be subdivided as indicated in Figure 1.

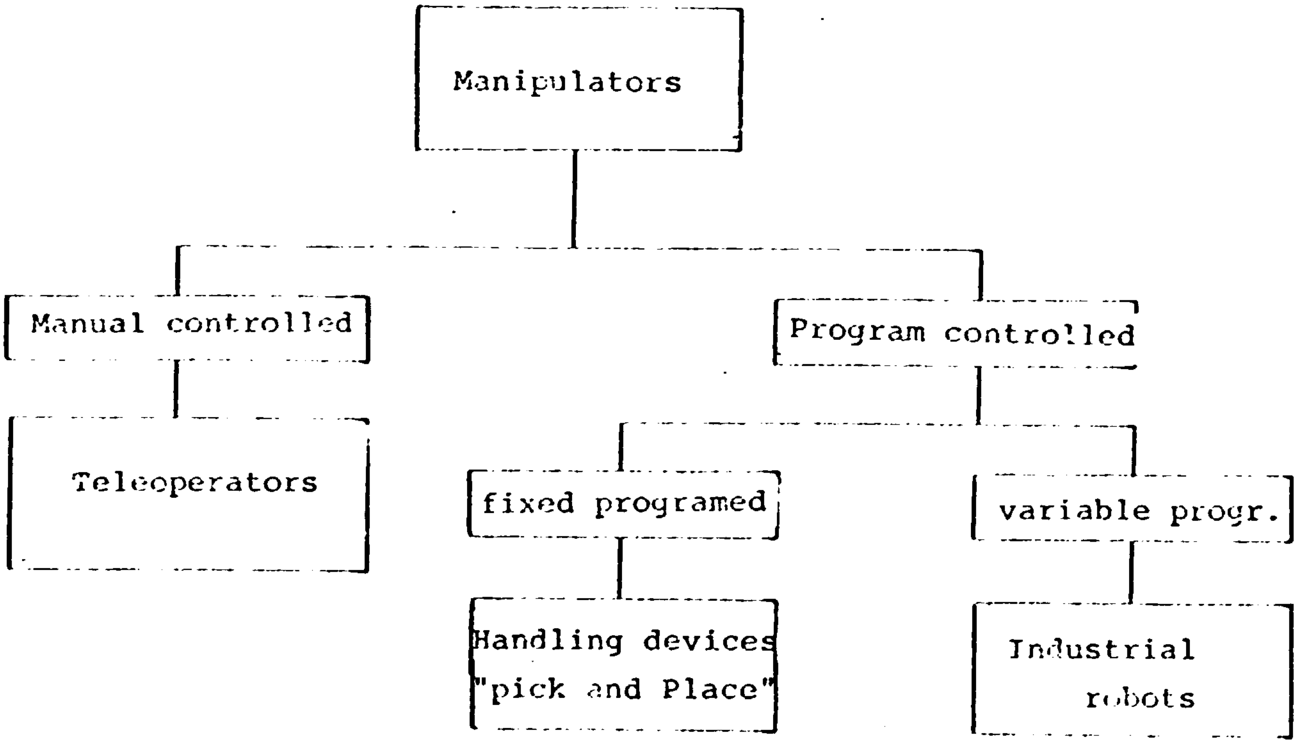

Figure 1: Manipulators

The simplest and also "classical" manipulators were developed for the nuclear technique. These "Teleoperators" were manual controlled by an operator.The other group of manipulators are programmable either fixed or flexible. The first category include all simple "pick and place" devices which are

applicated mainly for machine loading and for simple assembly operations. The second category - flexible programable manipulators- are called industrial robots.
From the various definitions which are used today two will be given in the following:
The first was proposed by the International Organization for Standardization (ISO)

> " The industrial robot is an automatic position-controlled reprogrammable, multi-functional manipulator having several degrees of freedom capable of handling materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks"

Very close to this ISO definition is that used by the British Robot Association. According to the Japanese Industrial Standards (JIS) a robot is defined as

> " A mechanical system which has flexible motion functions analogous to the motion functions of living organisms or combines such motion functions with intelligent functions, and which acts in response to the human will. In this context, intelligent functions mean the ability to perform at least one of the following: judgement, recognition, adaption or learning."

The key words in these definitions are programmable or reprogrammable and variety. Robots can easy programmed for a number of different functions, whereas automated machines are designed exclusively for a specialized function.

Robots can be classified from various points of view. Some of those are:

- Load capacity
- Arm geometry (kinematic structure)
- Drive system
- Control system
- Accuracy

Load capacity: Usually the robots available today are subdivided in the following groups: less than 2kg, 2 to 20kg, up to 100kg and over 100kg. The maximum load capacity today amounts approximately 1000kg.

Arm geometry: According to the human hand the robot has to realize 6 degrees of freedom. From these the arm has to realize usually 3 degrees of freedom. These can be either translatorial (T) or rotational (R). In Figure 2

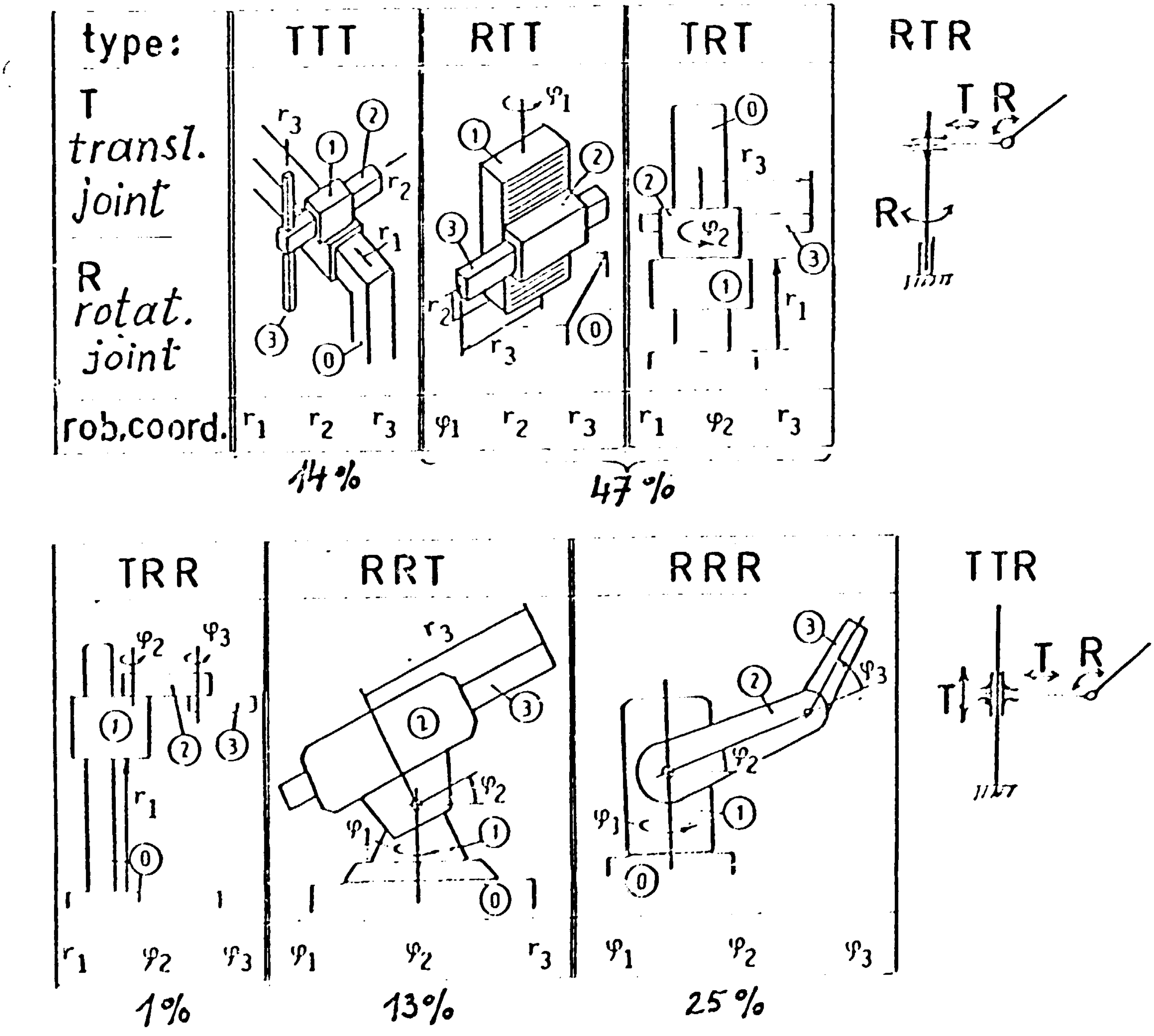

Figure 2: Arm kinematics of industrial robots

the most frequently used structures are collected together with their working space and the percentage of using.

- Arm with three translatorial degrees of freedom, type (TTT), cartesian robot: The gripper moves in three different directions controlling the height, the width and the depth of the operation. It gives the arm a great accuracy but makes it slow.14% of the robots used today are of this type.
- Arm with one rotational and two translatorial degrees of freedom, type TTR, TRT or RTT, cylindrical robot: While the type TTR isn't used today the other two kinematic structures (TRT,RTT) are frequently applicated. 47% of the robots used today are of this structure
- Arm with two rotational and one translatorial degree of freedom, type TRR,RTR or RRT, polar or spherical robot: Only the latter two types are now in application (14%).
- Arm with three rotational degrees of freedom, type RRR, revolute or antropomorphic robot: These are the most flexible of robotic arms, capable of reaching nooks and crannies that others cannot (25%).

For different applications, different configurations may be appropriate. A revolute arm might be the best for reaching into a tub,while a cylindrical arm might be the best suited to a straight thrust between the dies of a punch press.

In every case the arm carries a wrist assembly to orient its end effector as demanded by workpiece placement. Usually the wrist realizes the other tree degrees of freedom necessary for reaching each point in the working space with a predeterminated orientation. In the case of three rotational degrees of freedom these are labeled pitch, yaw and roll analogues with the aircraft terminology. In many cases ,depending of the type of work, the geometry of the workpiece etc. the robot is able to work with less than six articulations. The total number of degrees of freedom (the number of axes) is together with the size of the working space, an indication of the degree of versatility

<u>Drive systems:</u> Each robot articulation requires an own drive system. Robot drives can be electrical, pneumatic, hydraulic or some combination of theses

- Pneumatic drives use compressed air, are lightweight, fast and relatively inexpensive. Unfortunately these drive systems are very difficult to control of either speed or position, two essential ingredients for a sucessful robot. Therefore they are mainly used for simple pick and place devices with little load capacities. They are found in approximately 25% of robots.
- Hydraulic drives works with compressed fluids, are more expensive than pneumatic drives but much stronger. One disadvantage might be the leaking. On the other hand advantageous is the compactness of the drives, the high levels of force and power together with an accurate control. Approximately 30% of the robots are driven hydraulically.
- Electric drives are used in approximately 40% of robots. Typical forms are servomotors, stepping motors, pulse motors, linear solenoids and rotational solenoids. They are the strongest, least energy consuming but the most expensive robot drives. The control is very easy and accurate.

While the pneumatic drive has a strong defined application area the crossover point between hydraulic and electric drives may vary with robot configuration and the robots intended use. Every drive has its advantages and disadvantages and will eventually find its proper place.

Control system: The control system for a robot is extremely important and usually quite complicated. The main functions of the control system are

- the position control of each arm (servocontrol),
- the trajectory computation,
- sensor processing,
- program interpretation and
- external links.

Robot controls typically use one or more microprocessors internally to implement these functions. Not all robots or applications require all these five functions

- Position control (servocontrol): From the point of view of control robots can divided into two main groups

  a) Open loop controlled (nonservo-controlled) robots and

  b) Closed loop controlled (servo-controlled) robots.

Open loop controlled robots have no feedback of the actual positions of the arms for evaluation or correction. Their motions are determined by a simple sequence controller and mechanical hardstops or limit switches. Robots utilizing this technique can be cost effective for repetitive tasks with a limited number of motions.

Closed loop controlled robots are equipped with encoders or resolvers on each axis provide the current position information. Comparing the current position to the commanded position and driving the actuator to eliminate the difference forms the basis for the control.It provides the most flexible form of control and is widely used for industrial robots.

In point to point (PTP) control each arm is controlled by an independent position controller. Between preprogrammed points each joint freely runs at its maximum or limited rate until reaches its final position. There are three ways of controlling point to point motion independently:

- sequential joint control (PIS-S): Only one arm at a time is activated
- uncoordinated joint control (PIP-U): All arms are activated but there is no coordination of motion between points
- terminally coordinated joint control (PIP-T): The individual arm motions are coordinated so that all arms attain their final positions simultaneously.

Continous path control: This type of control is used where continous path of the "handpoint" or endeffector is of primary importance to the application. This motion is produced by interpolating the control variables for each arm from its initial value to its desired final value. All joints complete their motions simultaneously yielding to a coordinated joint motion.Continous path control techniques can be divided into three basic categories based on how much information about the path is used in the control calculations:

- conventional control approach: The controller have a stored representation of the path it is to follow.

- "feed-forward control"(preview control): The controller uses some informations about how the path changes immediately ahead of the robot current location.

- "path planning" ("trajectory calculation") approach: Using a mathematical "model" of the arm and its load, the controller precomputes an acceleration profile for each joint. This approach has been used mainly in advanced robots.

- Trajectory computation: Complex mathematically, it draws heavily on the computational capabilities of the control computer. The control computer have to determine the proper combination of movements of each axis or joint so that the resultant combined displacement produces the desired motion. A central aspect of trajectory computation is the conversion from robot coordinates (angles or lenghts of the joints) to world coordinates (cartesian coordinates of the handpoint) and vice versa. Another problem is the calculation of the "optimal" acceleration/deceleration profile. Overshoot is undesirable, but too conservative a profile may slow the robot unnecessarily.

- Sensor processing: Sensors alert the control to activities and events beyond the robot. Based on this knowledge, the control can adjust the arms trajectory, coordinate activities with other machines, or recognize error conditions. Sensors such as for vision and force measurement produce additional,complex input signals to the robot control. By monitoring a force sensor, the robot control can cause the arm to follow part edges or overcome assembly jamming points. Similarely, constant sensor monitoring during arc welding prompts adjustment of the trajectory to fill in part gaps.

- Program interpretation: The robot program is the sequence of commands or steps that the robot should follow to accomplish a task. There are mainly two ways to create a program:off-line and on-line. On-line programming (teach mode) is done on-line using the robot. The robot is moved in the desired positions either by hand (direct teach in) or by the drives actuated by a teach pendant, a joystick or a master slave device (indirect teach in). These points are stored and also the whole sequence. This method is very easy to learn, but it ties up the robot during the teaching and it can be tedious for long or complex programs.

Robot programms can also be prepared off-line without using the robot. The operator enters commands by means of a terminal in a robot programming language. The programs can now prepared without disturbing the robots operation and complex tasks involving extensive branching or sensors are much easier to program. On the other hand the knowledge of a distinct programming language is necessary for the operator

- External links: Links between the robot controller and an external computer are offered at the most commercial available robots. There are several reasons for including this function in a robot control. One common motivation is the desire to storage robot programs on a large host computer eleminating the need for storing media like cassette tapes at the robot. Another reason could be the connection to a CAD/CAM system.In this instance the geometry data stored in the CAD/CAM system defines the robot tool path. Creating the robot program with the CAD data reduces the robot programming time and minimizes the chances for error. As an added benefit the graphic terminal can display an animation of the completed robot program for detecting inefficient cell layouts, probable collisions between the robot and the workplace and joint limit checks. The robot control computer could also used collecting datas for maintenance and production control.

Accuracy: Experiences has shown that the accuracy depends mainly from the load capacity and the dynamic performance. Robots with a higher load capacity have also a larger working space and are therefore less accurate than small sized robots. It is also quite logical that, with a heavier load (moment of inertia), a higher operational speed or a larger operating space, it is more complicated and expensive to attain the required accuracy. Very close to accuracy is reliability and safety. Reliability is defined as the capability of an industrial robot to perform the given task under specified operating conditions. The main safety requirement is the guarding and protection of the whole working area and the prevention of unauthorized access. In this connection, appropriate training of personel entering the guarded area to perform their functions is also required. More than 60% of industrial robots used today guarantee a positioning error of less than 1mm.

Some of these classification characteristics mentioned before are identical with the main parts of an industrial robot wich are shown in Figure 3 also in form of a block diagramm.

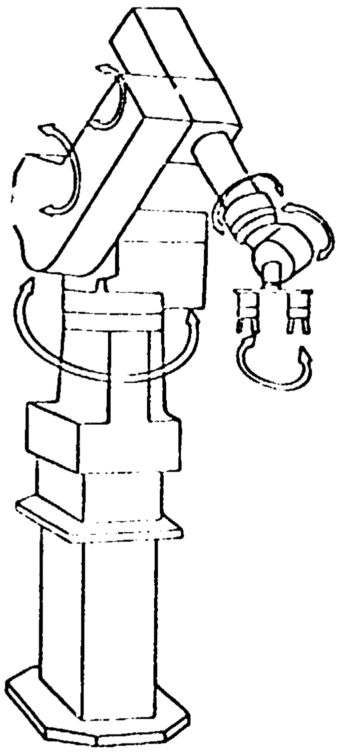

Figure 3a: The robot

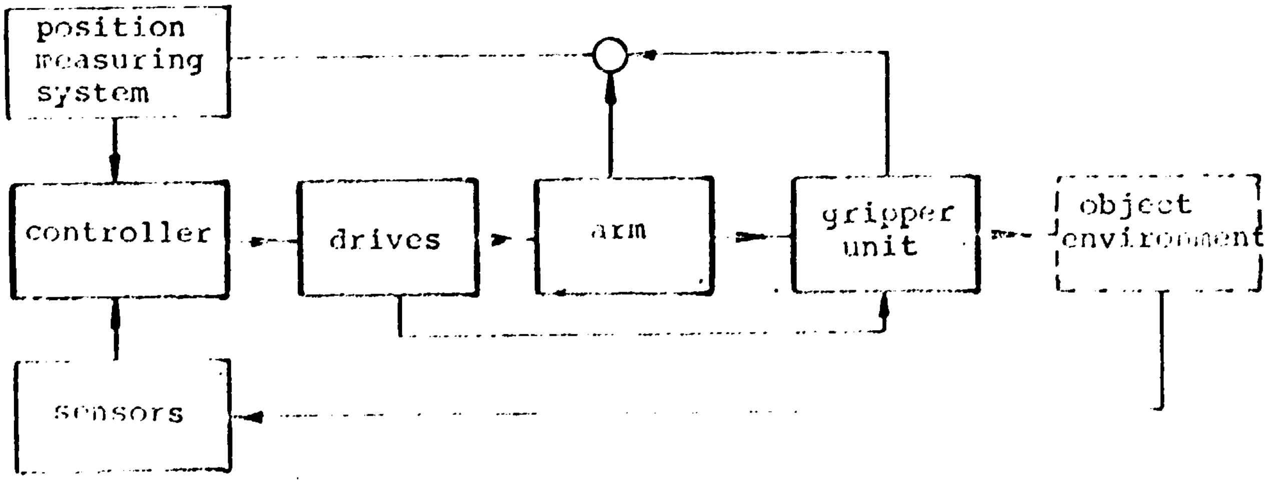

Figure 3b: Main parts of the robot

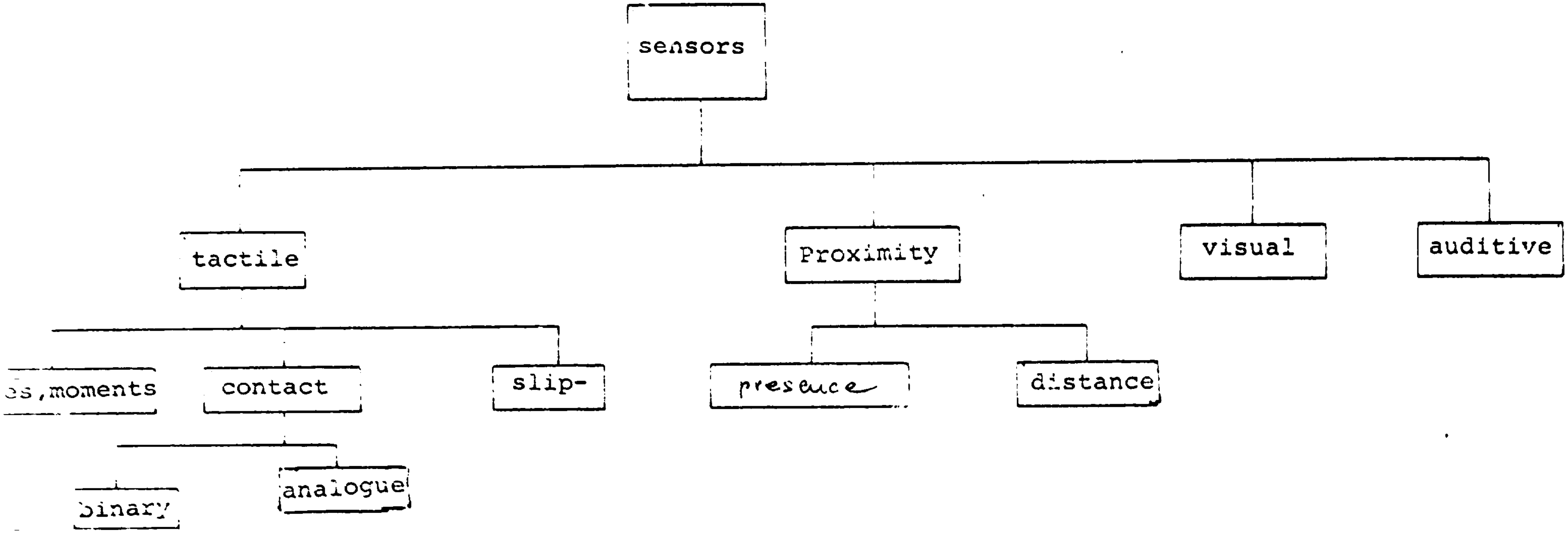
sensors
tactile
Proximity
visual
auditive
es,moments
contact
slip-
presence
distance
binary
analogue

Fig. 4

These parts explained in detail, are the arm, the drive including the gear and the control computer.Additional parts are

-the gripper including the gripping device
-internal sensors or position measurement system
-external sensors.

As pointed out earlier the gripper realizes usually three degrees of freedom. These can also be either translatorial or rotational. A important part of an industrial robot are the gripping devices or end effectors. These are mounted at the last link of the gripper and are the moving components which have to grasp, lift and manipulate workpieces or tools. Being less adaptable than human hands, robot hands have to be chosen or designed specially for particular industrial application. These "hands" are less flexible and may have to be included along with the special tooling requirements of the job. Most of the hands used today are without any sense of feeling or touch. In developping are sensor equipped hands.
Internal sensors are mounted on each joint for giving the actual position in robot coordinates. Encoders, resolvers or other devices on each robot axis provide current position information.
External sensors: As pointed out earlier "intelligent" robots of the future have to be equipped with sensors. These sensors give the control computer of the robot additional informations about the surrounding. As shown in Figure 4 external sensors available today may be assigned to four main groups:

- tactile sensors serve for measurement of forces and moments usually between the gripping device and the object or between the gripper and the end effector.
- proximity sensors deliver informations about presence, distance, speed of approximation ... They are working without contact.
- visual sensors are of great importance for tasks in

connection with assembly operations (part identification, orientation...).They are working mainly with TV cameras.

- auditive sensors are now in development and serve for speech recognition.

2. Main areas of robot applications.

While the last chapter of the present information package deals with problems of robot definition, of robot anatomy, of robot control etc. In this chapter which is based on generally available information sources,a brief review is given of the field of application.

Today there are mainly two reasons for the application of industrial robots

- Rationalization
- Humanisation

The rationalization effect results from different facts e.g. increasing of the flexibility of manufacturing devices, increasing and uniforming of the product quality, increasing of the productivity. The effectivness of each robot application will be also affected by costs resulting of periphal devices,installations, room and energy, programming, maitenance, personal education. On the other hand lower salary costs, a higher productivity, a better and constant quality are obtained in the most cases.

From the viewpoint of humanisation the application of industrial robots yields to elimination of the worker from monotonous actions, deliveration of the worker from noxious environmental facts (heat,dust,noise..), increasing of the wporking satisfaction, increasing of the security at the working place.

Therefore the major application areas of industrial robots include:

- Pick and place type operations, in which case simple point to point controlled devices are usually sufficient.

Examples for those operations are machine loading and unloading, simple palletising, glass handling, brick manufacture, press work, packing and package distributing, warehouse service, foundry work, heat treating, coating and electroplating, investment casting, die casting, forging and metal coating.

- Welding robots, which are the largest in terms of population since the automotive industry employs the greatest number. Point to point as well as continous path controlled robots were widely applied applied for: spot welding, arc welding, seam welding, flame cutting, laser welding and plasma cutting.

- Machining robots requiring a rigid body and arm structure with adequate positioning repeatability. They have often to change tools and/or hands to accomodate different jobs. Machining applications include: drilling, routing, sheet metal fabrication and composite materials manufacturing.

- Cleaning and deburring applications with special purpose tools. Such robot applications often need adaptive force feedback sensing as well as automated robot tool changing.

- Spray painting applications.

- Automated assembly and inspection, which is probably the most interesting and fastest growing area of applications. This is due to the potential of the rapidely growing market of the assembly industry and its complexity in programming, tooling, sensory feedback processing, interfacing with other devices and communicating with remote computers.

In the following a short survey on applications of industrial robots will be given. The applications mentioned before are assigned to five groups

- Spot welding
- Arc welding
- Spray painting
- Assembly
- Materials handling

Spot welding applications:

In spot welding metal pieces are joined at a number of spots. This is accomplished by passing a large electric current at low voltage through the metal.The materials to be joined are clamped between copper or copper-alloy electrodes between these the current flows. In this small area localized heat is produced and the pressure exerted by the electrodes is joining both workpieces. Parameters affecting the quality are the current intensity, the welding time and the pressure.

Over the past decade the main application of industrial robots througghout the world has been in the field of automotive spot welding. 1969 General Motors had installed a line of 26 robots for spot welded car bodies and this was followed in 1970 by Daimler Benz with one robot for a bodyside spot-welding operation. From those beginnings the number of robots increases. An efficient application is ensured in most cases for medium series. For small series the peripheral devices are too expensive and therefore a manual welding is to prefere. Large series are welded by means of multiple point welding machines. One of the main advantages of the robot is the flexibilty which allows the welding of different workpieces e.g. different car bodies. Additional equippments for a spot welding robot are the gun, the supply for cooling water and welding current and the transformator. Usually these robots are programmed by direct or indirect teach in.

A spot welding robot should have the following features:

- 6 or 7 preferably rotational degrees of freedom (arm of type RRR)
- stiff but small construction

- load capacity from 60 to 100 kg
- accuracy less than 1mm
- simple programming
- high maintenance

Arc welding applications.

In this process the heat required to fuse the metal surfaces together is derived from an electric arc. The temperature in the vincity of the arc rises rapidely to as much as 6500 deg.F. At these temperatures a small pool of molten metal forms in the work, and the end of the electrode also melts to contribute additional metal to the pool. Therefore the electrode have to be electrically conducting and compatible with the material welded. A typical form is a metal wire continously fed. Starting with carbon electrodes more advanced techniques are used today. Examples are the so called Heliarc process , the Tungsten Inert gas process (TIG) and the Metal Inert Gas technique (MIG) also known as Gas Metal Arc Welding (GMAW). Therefore arc welding equipments comprises a gas line through which the electrode wire is threated. The line and the wire terminate in a welding gun. Control equipment propels the wire through the gas tube and governs its rate of travel. The direct current necessary for these methods is usually in the range 100 to 200 amperes and 10 to 30 volts. Control is also necessary for ensuring an optimum distance between electrode and workpiece. Good electric arc welding requires close control of the welding gun along the weld path, both in position and speed.

Some of these tasks have to be carried out by the robot. It job is mainly to guide the gun around the programmed path with the desired orientation and to signal when it is ready to proceed. The welding unit controller does the rest. Arc welding robots have usually implemented progams for moving the gun in form of a straight line between two points or in form of a circle given by three points. A path is programmed by storing of a sufficient number of points. The control computer calculate additional points for creating the desired path with sufficient accuracy.

Spray painting applications:

Painting is the coating of surfaces with a liquid mixture for the purposes of decoration or protection. Today spray painting by means of pressured air and a spray gun is commonplace in the industry especially in the automotive industry. The path of the spray gun is not defined precisely. It depends mainly of the experience of the operator. This technique is more an art than a science. The spray painting environment has always had the reputation of being one of the worst which human operators have to encounter.

For spray painting the path is important. Its end points are unimportant since a paint trajectory could theoretically start and finish outside the confines of the workpiece. Tharfore for these applications robots with continous path control (CP-robots) are necessary. The robot have to emulate nearly the action of an experienced paint sprayer with a positional accuracy better than 2mm. The programming of the robot have to be done by an expert who, with the robot on low power so that the arm is more or less weightless, leads the unit through movements necessary to give the workpiece a coat of paint.

Programs are changed by removing tape cassette and replacing it by another so that, if necessary, many hundreds of different programs can be stored away as the robots repertoire increases. The main advantages using robots for spray painting are:

- Dealing with a hostile environment (noise, carciogenic materials,particulate matter)
- Processing with less energy (reducing fresh air requirements,reducing exhaust).
- Improving paint quality (less dirt, uniform build, consistent quality level, cope with specialized spray techniques).

These facts yield to reduced material costs, reduced warranty,reduced in-house repairs and reducing direct labor costs. To meet the demands of what will clearly be a lucrative market,several robot builders are preparing their robots for this application, and competition may be fierce in the years

Assembly applications:

The automated assembly is one of the fields with the highest estimated growing rates. Assembly operations are mostly very difficult for robots. Therefore the robots which were available until now (robots of the first generation) are not equipped with the necessary "intelligent" abilties.
Today automated assembly by means of robots is limited to very simple operations with few parts. Restrictions for robot application in this field are given by

- the parts have to be isolated (the "grip in the box" is not possible in practice)
- industrial robots suited for assembly operations must have either sensors or an extrem accurate position control
- parts with little differences in the surfaces require expensive visual recognition systems.

Today some robots with the necessary capabilities for assembly operations will be developped and few of them are already available. Because of ecomomic reasons simple assembly operations are carried out today by means of "assembly machines" with less flexibility. These assembly machines are equipped with primitive pick- and place robots with high accuracy (less than 0.01mm) owing to the mechanical hardstops or limiting switches. This assembly machines are mostly a combination of various modules for ensuring a possibly high reuse value.
There is a great concentration of worldwide research activities with the goal to make the robots a bit more sensitive for assembly operations.

Material handling applications:

For most of these operations simple pick- and place robots are necessary. Material handling by industrial robots is carried out in various industries on different machines (e.g.casting machines, forging machines, presses, plastic machines, foundry machines, machine tools, brick machines, glass machines....). The loading and unloading of machine tools is already a classical field for using robots. One problem are the parts with a great variety of surfaces, geometric forms and materials. This spectrum requires different endeffectors (gripperhands) as well as various feeding and arranging devices. For loading of one machine tool a robot with 4 degrees of freedom and an arm structure TTT or RTT will be sufficient in most cases. Linking of more machines requires more complex robots with 6 or more degrees of freedom and a kinematic structure RTT or RRR. In this case the control computer of the machine and of the robot must be coupled. In the future the robots have to serve more machines witch are possibly arranged in flexible production cells. For this purpose the robots should have

- a large working area
- a high load capacity
- more than five degrees of freedom
- flexible gripping devices
- sufficient storage capacity in the control computer

For feeding of presses a high flexibility of the robot is necessary. This results mainly from the small or medium series (10000 to 50000 parts) and the small cycle times (2 to 10 seconds). Therefore frequently retooling is necessary. Special requests on the robot are

- large working area
- quick and simple programming
- additional functions for control of press functions.

In most cases press feeding is an application field with inhuman working conditions e.g. noise (80 to 100dB(A)), high temperatures (up to 500 deg on the gripping device) especially at forging presses. Similar problems arise by casting machines and processes.

Various other applications:

Other applications of industrial robots are deburring of metal parts, grinding and polishing of surfaces (metallic and nonmetallic), cutting of nonmetallic materials (e.g.fibre glass-reinforced plastic) and palletizing operations. Each of these applications requires special features of the robot

3. Diffusion of robots into production.

The industrial robot-market is growing steadily all over the world. Robots are used in large manufacturing companies specialized in distinct fields (automotive industry, electrical industries) as well as small companies. The present chapter gives some estimates of the current world robot population and forecasts of its growth over the next decade. The level of international collaboration in this field is very high owing to licensing and intergovernmental agreements and the growing activities of transnational companies in this sector.

The total number of robots in service in 1981 has been estimated at 30,000 units, in 1982 at 39,000 units and in 1983 at 50,000 units excluding manual manipulators and equipment with a fixed, unchangeable sequence of operations. Including of non-programmable manipulators, the total number of units may be four to five times larger. If the present trend continues, i.e. if the total number of units is doubled every two years, around the year 2000 more than 10million robots could be expected to be in use /6/.

According to other sources, some 1 million robots can be expected to be in use by 1990. A more precise forcast published by OECD /6/ is presented in Table 1

Country	1981	1985	1990	Annual growth rate (percentage)	
				1981-85	1985-90
Japan	9 500	27 000	67 000	30	20
United States	4 500	15 000	56 000	35	30
Sweden	1 700	4 100	8 300	25	15
Germany, Federal Republic of	2 300	8 800	27 000	40	25
United Kingdom	713	2 700	10 000	40	30
France	790	2 100	6 500	28	25

Table 1: Estimate of robot population

The number of units in less optimistic forecasts are until half of them in the Table. Other estimations bases of annual growth rates of 20 to 30%.

Table 2 shows the countries which are include in Table 1 arranged in the order of the density of robots. According to these Table Sweden is the most "robotized" country followed by Japan and the FRG.

Country	Number of installed robots	Industrial workforce (thousands)	Density robots per 10,000 workers
Sweden	1 300	1 352	9.6
Japan	13 000	19 556	6.6
Germany, Federal Republic of	3 500	11 334	3.1
Belgium	361	1 322	2.7
United Kingdom	1 152	5 272	2.2
United States	6 250	29 774	2.1
France	950	7 574	1.25
Italy	700	7 787	0.9

Table 2: Robot installations and employment

Of interest could be the distribution of industrial robots in the application fields mentioned above. Unfortunately there are only numbers concerning distinct countries available. Therefore as a typical example the distribution of robots in the FRG is given in Table 3 for 1981 as well as a forecast for 1990.

	1981		1990	
	abs.	%	abs.	%
spot welding	800	35	3000	25
arc welding	230	10	2340	20
painting	230	10	800	6,5
assembly	100	4	2760	23
handling	520	23	1950	16
various	420	18	1150	9,5
Total	2300	100	12000	100

Table 3:Use of industrial robots in the F.R.G.

1981 approximately 35% of the robots were applied for spot welding operations- mainly in the automotive industry- 1990 the percentage will decrease to 25% while the arc welding will increase from 10% to 20%. As pointed out earlier the assembly application will have the highest growth rate (from 4% to 23%). The spray painting and handling operations decreases also. Despite high growth rates, the robot industry is still a relatively small industry. Total output in 1982 was only in the order of 3% of that of the machine tool industry. However, those aspects with make the robot industry important- one could even say strategic- are the following:

- It has avery high growth potential, which may in the long term, result in its becoming a large industry.

- It has become a symbol of factory automation in general and thus has a considerable indirect effect on the wide diffusion of factory automation equipment.

The robot industry is a high-technology industry which in some respects differs from other comparable high-technology industries such as microelectronics and telecommunications industries. These differences stem mainly from the fact that the development of robots, to a higher degree than that of the above mentioned areas, is based on the integration of a multitude of technologies from a variety of industries- machine tools, computers, process control, sensor technology, software and various kinds of application knowlwdge such as welding, painting, assembling etc.

4.Technical,economical and social implications related to the introduction of robots in developping countries.

The present decade is characterized by the rapid diffusion of microelectronics in industry which will lead to increases in labour productivity and to significant changes in the structure of jobs. One example for this development are the industrial robots. Robots have produced a number of economic and social changes. Among them are an improvement in productivity, greater humanization of working life, prevention of industrial accidents, improvement of product quality, and early return on capital investments.

These economic and social effects stemmed from the fact that industrial robots are flexible and versatile, featuring a greater freedom of movement similar to that of upper limbs (arms and hands) of human beeing. This has enabled the automation of small batch production, and the introduction of industrial robots has changed the production system from a man- machine-system to a man-robot-machine system. This change in production system means that people have been released from dangerous, unfavorable works.

As pointed out earlier the advantages of industrial robots are a high speed operation, reduced value of work-in progress, quick automatic resetting of equipment and tool changing, availability of equipments 24 hours per day and high reliability. Improved utilization of capital assets may also supplement economic benefits considerably:

- As the manual jobs and operations in which robots replace workers are naturally those that are most hazardous, physically and mentally demanding, tiring etc. It is obvious that the robot is generally more consistent on the job and its use will significantly increase net output

- The prime issue in justifying the introduction of robots is labour displacement,either by transferring workers and operators from hazardous working conditions to more convenient jobs or simply by saving labour costs.

- The introduction of robots significantly helps to meet the demand for higher product quality and a reduction in the time lapse between receipt and confirmation of the customers order and its filling. Manufacturng processes equipped with robots seem more competitive in the market, as has been proved in the automotive industry.

- Among the other economic effects, those concerning raw material and energy savings are most important. Automated material-requirement planning provides for optimum stock levels of various raw materials, assembly parts, semi-finished products etc. In addition to the optimization of energy consumption various organizational structures and processes may be simplified, such as maintenance, dispatching, transport, accounting, invoicing and other financial operations.

On the other hand,robot costs consists of:

- The purchase price of the robot installation, including accessories, peripherals etc.

- Maintenance and periodic overhaul.

- Operating costs.

- Depreciation (return rate of investment)

- Personal costs including training.

  Of interest for devoping countries will be the price of the robot. As mentioned before the price depends on the number of articulations, the working space, the loading capacity and so on. But it is a great difference between the price of the robot and the price of the whole "robot working place". In most cases the costs of the periphal devices amounts up to three times of the robot.

- Special tooling might include special conveyors, transformers, welding guns and special controlling equipments needed for the interface with the workplace.

- Any well-implemented robot system working approximately two shifts. Therefore a regular maintenance and a periodic overhaul are necessary. The annual costs for these purposes amounts approximately 10% of the acquisition costs but depends also on the job and on the environment.

- The operating costs include power requirements and therefore energy costs which are higher for automated manufacturing than for manual operations.

- It is mostly assumed that the "life" of the robot is 10 years. This yield to a payback of three years for one-shift operation and 1.5 years for a two-shift operation.

The sucessful introduction of robots into an existing plant depends of the "readiness" of those involved to accept new technology and adapt to new methods of work.

The industrialization in the 19th century was sometimes characterized by the term "first technical revolution". Now we have been since about twenty or thirty years in the period of a "second technological revolution" which is determined by cybernetics and systems approach. The microelectronics and therefore also the robots may be the begin of a "third revolution".

This technological process widened the scientific, technological and economic gap in the world between industrially developed countries and these in the process of such a development or still being in a pre-industrial state but with a quickly growing population. Difficulties may arise, too, when such modern production methods e.g. robots are introduced to quickly. Developing countries very often have a long history of advanced culture. By a brusque change to a modern industrial structure and the concentration of population in big cities such countries may loose their traditional identity. Other problems may arise when scientists and techniciens of these countries stay during their education for a long time in highly industrialized countries and then return to their home countries. They have to adapt themselves and the advanced technologies to the economic and technological situation in their countries.

Therefore an efficient introduction of industrial robots in developing countries requires first a developed infrastructure to enable modern production methods

This infrastructure might be influenced by the following factors:

- Government policies: This factor includes legislation, appropriations, or regulations that influenced the robot introduction in a country e.g. funding for research and development, antitrust and patent laws, procurment policies, market protection policies...

- Technological factors: These factors are basic for supporting the development of the robot introduction in a country e.g. research and development infrastructure, access to technology...

- Economic factors: These factors are decisive for the continuing success of robot and related firms e.g. venture capital, competition among producers, market characteristics, economics of scale and experience, wage rates...

- Cultural factors: These factors depend on geography, history and type of governement e.g. mobility of workers, producer-buyer relationships, commitment of employees..

Each of the described factors in the four groups needs to be considered carefully to determine whether it will facilitate or inhibit the development of industries equipped with robots.

5.Importance of application of robots in developing countries

As pointed out earlier the characteristics of the new technology associated to those of the robots, will lead, certainly, to changes in the whole production process. CAD/CAM technology combined with robots tends to become configurated in a totally automated plant designed to explore all the capabilities and the potential of the robots (speed, precision, versatility, e.t.c.). At present in the plants using robots, these are integrated into human-scale production methods. A more efficient way of robot application would be the building of new automated plants, based on programmed robots, capable of altering the scale and speed of the production function.

The application of CIM, CAD/CAM and of robots in the manufacturing process tends to alter the international division of labor and the relationship of competitiveness in the world market. These new production technologies permit producing on a world market scale, although the plants may be situated in a relatively small territory market (e.g. Hong Kong, Singapore, Taiwan) hundred or thousand miles away from another. The benefits of this development of the productive system will be appropiated, almost exclusively, by transnational conglomerates, who put into practice a new international division of labour, drawing from the comparative advantages of each country and region, where their subsidiaries are installed.

Under these conditions, projects integrated on an international scale, and based on complementarity and the exchange of parts and components become highly profitable, due to gains resulting from the transfer of technology, from under and over- pricing of exports and imports and from incentives granted by the governments of newly industrialized countries (developping countries) eager to attract foreign investments of risk capital.

The introduction and generalization of technologies based on microprocessors like CIM and robots result in reduction of capital per output unit, while representing an increase in the organic composition of capital, making the firms more capital-intensive. This yields to the mobilization of large resources for the formation of capital difficult to achieve in developping and even in the newly industrialized countries.

On the other hand, the proportional reduction of labor costs in the total cost of the final product, tends to reduce and, eventually, to eliminate the the advantage of lower wages in the developing countries. These made possible the production and export of consumer goods and manufactures goods in general in recent years. The widespread use of CIM and robots in integrated and fully automated processes, restores to the more developed countries, the means of competing in the production and sale of manufactured goods, previously highly labor-intensive (e.g. the textile, footwear and steel industries). Added to the problem of the fierce competition for markets in deep recession and crisis, is the fact that the newly industrialized countries (Mexico, Brazil, South Korea, etc.) structured their industries and manufacturing processes on electromechanical based technologies. With the penetration of microelectronics into all branches and sectors of ecomomic activity, machines and equipments invested become obsolete and prematurely depreciated, although the investment were made at the expenses of a heavy external and internal indebtment, with dramatic reflexes on the economic and political perspectives of these countries.

Furthermore, the new technologies as CIM and robots will cause the loss of innumerable jobs, besides the problem of a permanent structural unemployment.

These are some facts and ideas underlining the necessity for introducing new technology and especially industrial robots in developing countries.

6.Guidelines for the introduction of industrial robots in developing countries

Although a lot has been said about the transfer of technology, the appropriate technology, the soft technology in connection with robots and CIM as well as FMS. A glance at the subject will confirm that technology is related to many factors: to the scientific knowledge, to the culture, to the education, to the economy, to the history, to the geography, to the national resources, to the politics to mention only these.

Considering the existence of these relations, any attempt to acquire or to develop a national technology, or to use it for the wellbeing of a country or of humanity in general, could base itself on an approach which considers technology as an element in a complicated societal system.

For an efficient introduction of industrial robots in developing countries the classical procedure of systems approach might be used. This is summarized in Figure 5.

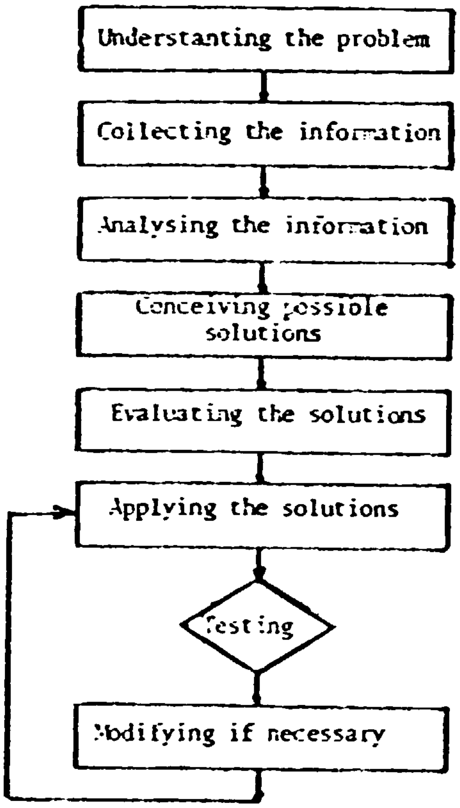

Figure 5:Classical procedure of system approach /5/

Beside these "technical" facts the following socio-economic problems have to be considered:

- Industry, government and unions must cooperate in economic and business planning at medium-long term, disclosing the emergent changes, and their impact on employment.

- The firms and industries most affected, must identify the most vulnerable categories of workers, well before their tasks become obsolete and are eliminated.

- Educational and training facilities ought be established, to recycle workers, eliminated from their jobs, for new qualifications required by the market.

- Firms and public administration should organize to offer adequate jobs to those who have been displaced from their work, paying if necessary, the costs of relocation.

- A special found, besides that of unemployment insurance, should be instituted, the resources to be used for defray the costs of the transport, supporting and training of dislocated workers.

Literature used for this introductory article

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/2/ Engelberger,J.F.: Robotics in practice. Kogan Page, London, 1981.

/3/ Zeldman,M.I.: What every engineer should know about robots. Marcel Dekker Inc., 1984.

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/6/ Production and Use of Industrial Robots. United Nations Publications, ECE/ENG.AUT/15, New York 1985.

The publications collected in section II

II. Selected Publications

Kep

The State of Industrial Robotics

What today's robots can do and what the future holds.

J. Michael Callahan
Jackson and Callahan Engineers
Old Colony Rd.
Eastford, CT 06242

Having grown up a fan of Isaac Asimov (see reference 1) and having watched countless reruns of *Lost in Space*, I always think of a machine with human characteristics when the word *robot* is mentioned. The image of R2D2 from the movie *Star Wars* must appear in many people's minds when they hear robot; however, robots that walk, talk, and exhibit other humanlike behavior are still not practical.

Today's industrial robot (the most common kind) is not as glamorous as some of us imagine, but it plays an increasingly important role in manufacturing. (The automobile industry is today's single largest employer of robots. Photo 1 shows three robots doing spot welding on an assembly line.) Present applications include but are not limited to spot welding, grinding, spray painting, machine-tool loading, and die casting. Some of the points covered in this article are the classification of industrial robots and a description of robot subsystems such as sensors, end effectors, control systems, and power/drive systems.

Also, I have described some robot manufacturers and the systems they sell. I have included references and a list of robot manufacturers so that if you are interested, it will be easier for you to obtain details.

Let me emphasize that the material presented here is only a description of the existing technology and is not meant to provide detailed design criteria. I will not be covering the sociological merits or shortcomings of industrial robots, nor the economic justification for the use of robots in a manufacturing facility. There are strong arguments both for and against the use of robots, and to deal with this issue fairly would take a separate article. As for the economics, I feel each particular application must be looked at in detail, and I do not want to take the time to de-

About the Author

Mike Callahan is a consulting engineer and general partner at the firm Jackson and Callahan Engineers. He specializes in energy systems analysis, energy management, microcomputer applications, and technical software.

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Acknowledgments

The author would like to thank Robert A. Lisak of New Haven, Connecticut, for taking most of the photographs used in this article. Both Ellen Mohr of Unimation and Joseph Blanco of ASEA made this article possible by providing detailed information about their systems and allowing tours of their facilities to get a firsthand look at their products. Additional thanks goes to Ellen for making available photographs 1 and 16.

Des

[illegible]

Photo 1: *Three Unimation robots welding on an automobile assembly line. Spot welding and arc welding are two areas in which robots are used extensively by the automobile industry.*

velop a representative example. If these topics interest you, see references 2 and 3.

Definition and Background

The Robotics Institute of America defines a robot as "a reprogrammable, multifunction manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks." The key words in this definition are *reprogrammable* and *variety*. Robots can be programmed for a number of different functions, whereas *automated machines* are designed exclusively for a specialized function. Therefore, in some applications, robots are superior to fixed-task automation. Robots can execute a series of spot welds during the assembly of a particular car model and can easily switch welding patterns as required for other models. No retooling is necessary. As a matter of fact, if a robot is no longer needed for welding it can be reprogrammed for other functions such as tool loading or material handling.

Unimation Inc. of Danbury, Connecticut, introduced the first industrial robots to the U.S. during the 1960s for use in die casting. Later, Unimation became the leading U.S. robot manufacturer and, in 1981, had $56 million worth of sales and more than 5000 robots in operation worldwide. A number of other companies also manufacture or distribute industrial robots in the United States, among them Cincinnati Milacron of Cincinnati, Ohio, and ASEA Inc., a Swedish company with offices in White Plains, New York. ASEA's Industrial Robot Division is one of the major participants in the U.S. robotics market. This year it has added four engineering centers and a new manufacturing facility. A number of large U.S. firms have also announced plans to enter the market, the most notable being General Electric and IBM.

At the end of 1981, an estimated 14,000 robots were in operation in Japan, 4400 in Western Europe, and 4100 in the United States. Even

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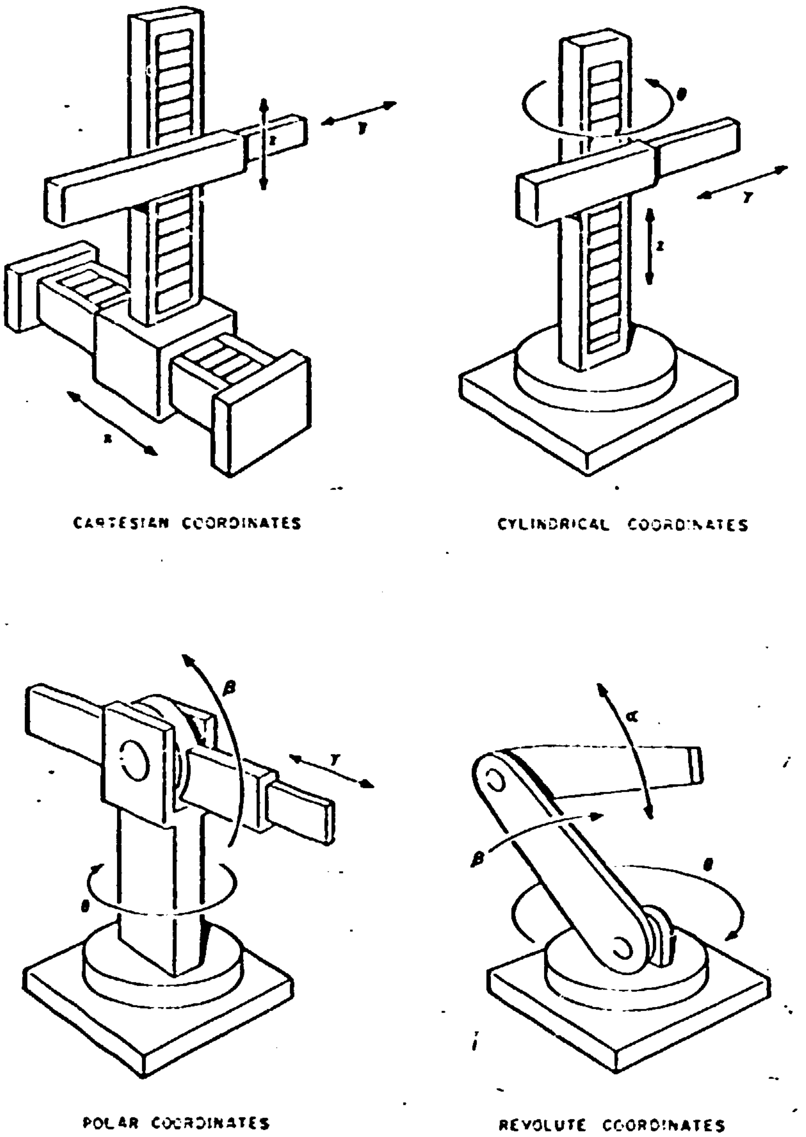


CARTESIAN COORDINATES

CYLINDRICAL COORDINATES

POLAR COORDINATES

REVOLUTE COORDINATES

Figure 1: Four different arm geometries used in robotics. In order to move the end of the robot arm to any point in space, there must be at least three degrees of freedom.

though U.S. robot manufacturers feel they lead in research, they admit that the Japanese lead in the application of robotics, for a number of reasons. In Japan, the government demonstrates an active interest in robotics because robots increase productivity and enhance the Japanese economy. There is also a shortage of labor in Japan, so the workers are not as resistant to robots as American workers. In fact, Japanese workers often willingly accept robots in the workplace. U.S. management is usually focused more on short-term profit than on long-term planning and, therefore, is less able to respond appropriately to productivity declines. Future projections place total robot sales for the United States at over $1 billion in 1990.

Robot Fundamentals

A way of classifying robots is according to their level of technological sophistication. The first category includes low-technology robots that are not *servo* controlled (i.e., their movements are powered directly, with no feedback or self-correction), have a limited number of program steps, and usually demonstrate good repeatability. The next category includes medium-technology robots that utilize servo mechanisms for accurate position and velocity control. These robots contain microprocessors or minicomputers as the basic control element, and because of the flexibility associated with the digital computer, you can easily reprogram their sequence of operations. (Today's robots, which are featured in this article, fall into this second category.) The last level of classification includes high-technology robots with all the features of medium-technology robots but with one important addition, external sensors that provide information about the external environment and considerably enhance performance. Video cameras, proximity sensors, and tactile sensors are examples of external sensors that might be found on advanced robots. Only a few robotic systems in operation today incorporate external sensors, and these should still be considered experimental.

In order to be useful, a robot must have the following attributes:

- a hand to grip a workpiece
- an arm to move the hand in three planes
- a wrist with two or three articulations
- sufficient power to move limb and workpiece around
- manual controls so that an operator can control limb motions
- a memory to store a sequence of instructions
- a means of executing a sequence of instructions stored in memory
- ability to function at speeds equal to or greater than a person
- reliability

The above attributes are provided by two major component systems in an industrial robot: the power/drive components (such as the arm, wrist, and end effector) and the control system (consisting most often of a digital computer and feedback sensors).

The primary purpose of the power/drive system is to position a tool or other end effector anywhere in the sphere of influence of the robot. In order to accomplish this, a robot arm must have at least three articulations. Figure 1 illustrates the different possible arm geometries that are used

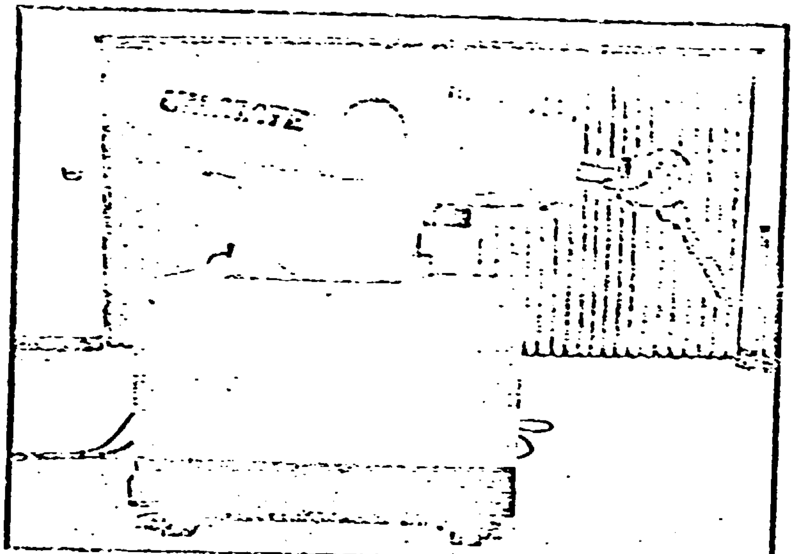


Photo 2: *The Unimate 2000 is a good example of a robot with polar-coordinate arm geometry.*

Photo 3: *The ASEA robot model number IRb-60 shown here at the ASEA application laboratory in White Plains, New York, illustrates the revolute-arm geometry.*

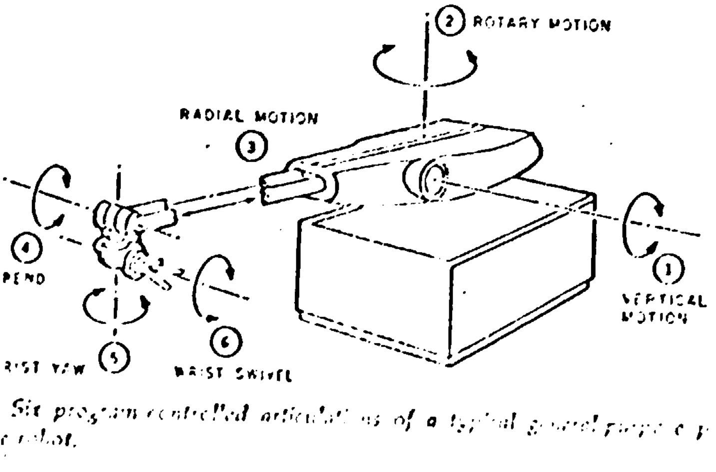


Figure 2: *Six program-controlled articulations of a typical general-purpose polar-coordinate robot.*

in robotics. Each geometry has its advantages and disadvantages depending on the particular application. For example, the revolute-coordinate configuration would be more appropriate for picking parts out of a bin, while a polar-coordinate system would be more appropriate for transferring parts between metal-cutting machines. Photos 2 and 3 show robots with polar-coordinate and revolute-arm geometries.

The most general-purpose robot will have six *degrees of freedom* as illustrated in figure 2. As well as having the ability to move the end of the arm to a specific point in space, the robot should have three more articulations at the wrist in order to orientate the end effector for the job at hand. Photo 4 shows a wrist with three articulations: swivel, yaw, and bend.

Usually, two methods are used to move the elements of a robot. Hydraulic drive is used for large robots where heavy loads are encountered, and electric drive is used in smaller robots where accuracy is important. This is not a hard-and-fast rule but, in general, is true. Pneumatic drive is sometimes used on robots but, because of poor position and speed control, is less popular.

Hydraulics is a popular drive method because hydraulic cylinders and motors are compact and provide high power and force. With proper feedback, hydraulic drives can offer good position and velocity control. A Unimate 4000, shown in photo 5 with its cover off, is a good illustration of the mechanisms of a hydraulic-driven robot. Hydraulic cylinders that provide a linear motion are often used in robots because they are inexpensive and reliable. Photo 6 showing a Unimate 4000 undergoing a test with a 450-pound weight should give you an idea of the lifting capability as well as the mechanical complexity of a hydraulic robot.

The electric-drive method for robots with less demanding lifting requirements primarily uses motors with gear trains or linear actuators. Where position accuracy is essential, electric drive is usually the appropriate and cost-effective choice.

Photo 4: *Three wrist articulations are usually required to position an end effector. Bend, swivel, and yaw motions are possible with the configuration shown here.*

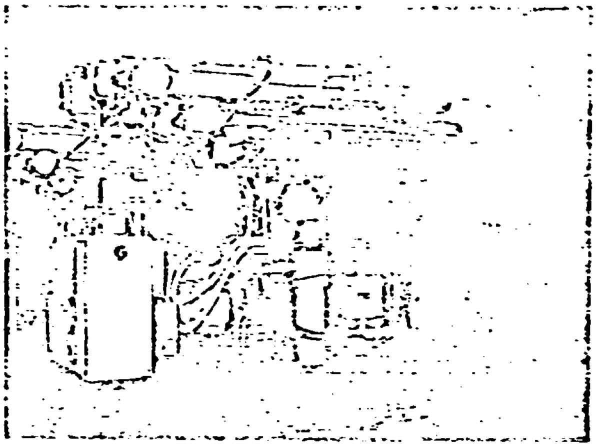
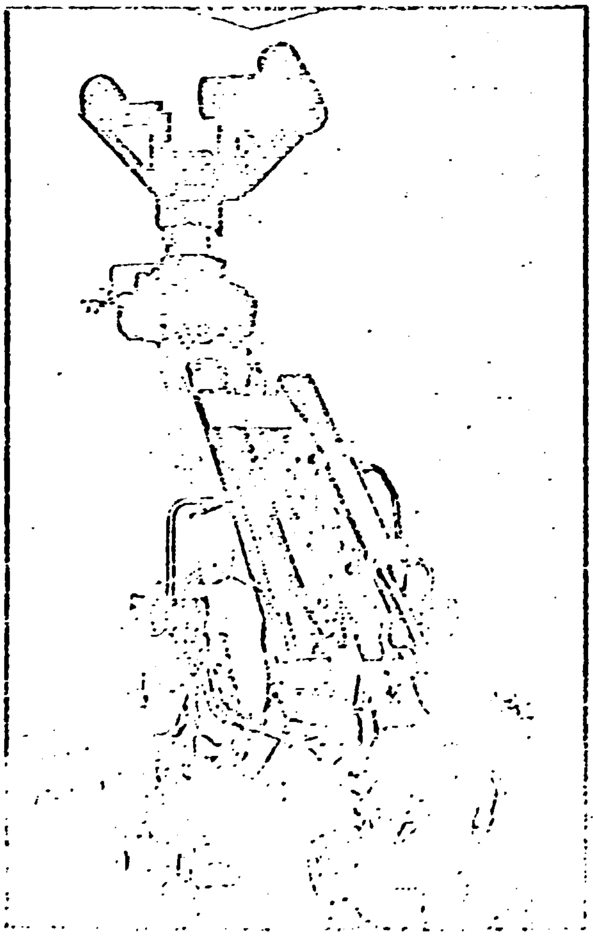


Photo 5: *The design and engineering of a hydraulic robot is not a trivial task, as is demonstrated here.*



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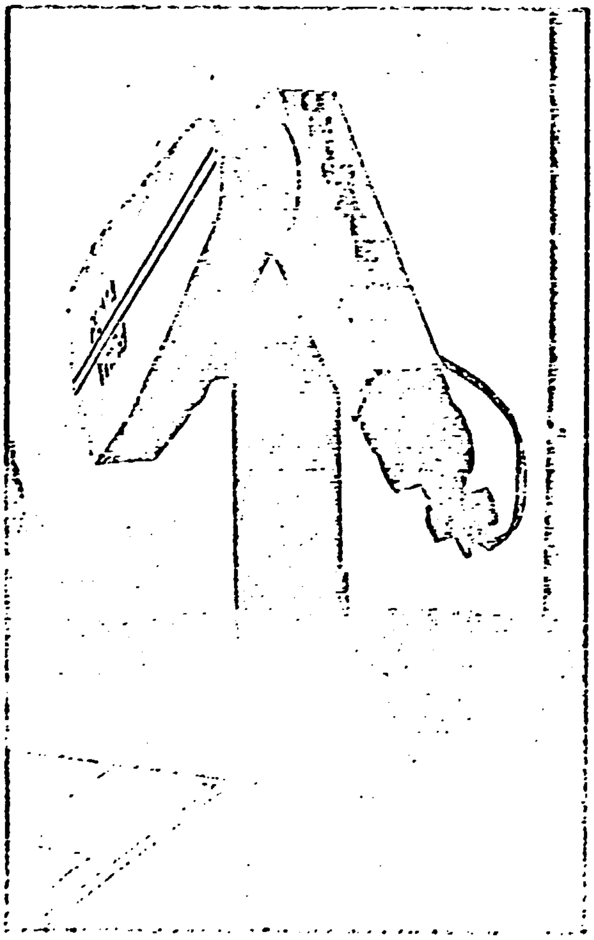

Photo 7: *The [illegible] Puma robot [illegible]*

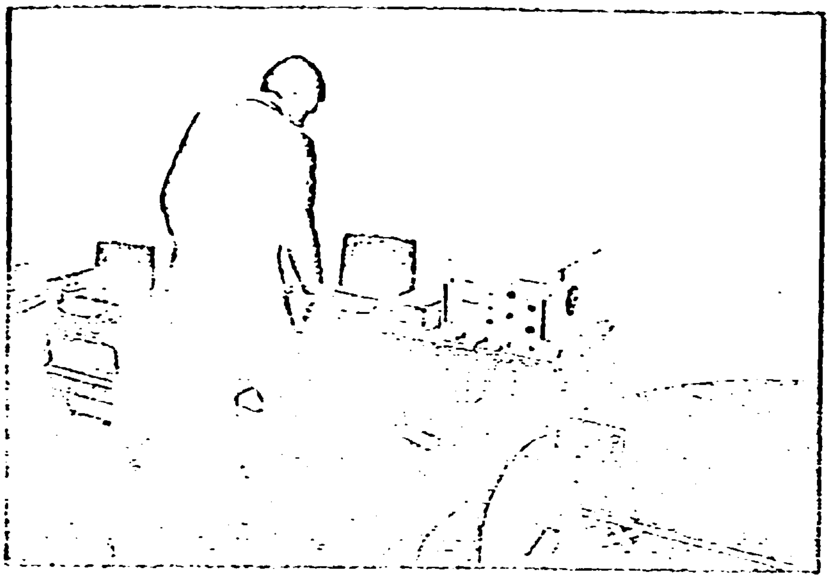

Photo 8: *The control system of the Puma robot resembles a personal computer system.*

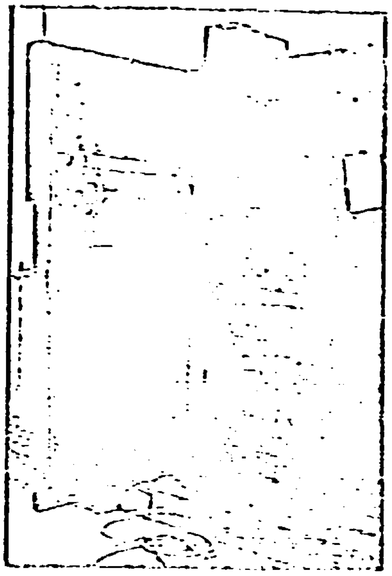

Photo 9: *The complexity of an electromechanical control unit is illustrated by this inside view of an ASEA model number IRb-6 control console.*

The ASEA robot shown in photo 3 uses an all-electric drive.

The control system for a robot is extremely important and usually quite complicated. The main function of the control system is to direct the motions of all the robot's elements. It must allow for human override as well as automatic operation. Another function is to allow for a sequence of instructions to be entered and then executed.

At present there are two methods to program the movements of a robot. The first is for a human operator to move the robot through the appropriate sequence of motions, using the manual controls. The control system "remembers" this sequence then plays it back at a later time. This can be viewed as teaching a robot a set of operations and allows for very easy programming.

The second method uses explicit instructions. The motion of the robot is controlled by issuing a sequence of commands that the robot understands. One command might be to move the end effector to a specific point in space, which would require that the robot interpret the instruction and generate control signals that move the limbs in such a way that the end effector moves to the correct place.

With a control scheme using explicit instructions, you can program the velocity and acceleration of each movement and choose the path the end effector will take. Unimation has a commercially available robot language called VAL that uses this programming method. Currently, VAL controls Unimation's small electric-driven robot, the Puma, which is shown in photo 7.

The control system for the Puma is shown in photo 8. The control system is like a small personal computer system. Note the keyboard, video display, and floppy-disk drive. The complexity of the control system and power/drive circuits for an electromechanical robot is illustrated in photo 9, which shows the inside of the control console for the ASEA model number IRb 6 robot.

End effectors are one of the major reasons robots are so versatile. Robots use end effectors for grasping, welding, gluing, and spray painting, just to mention a few tasks. The requirements for grippers are numerous and can be very specific. For forging applications, heavy-duty grippers that can withstand great temperatures are needed. Handling flat metal sheets requires either vacuum or magnetic grippers. For machine-tool loading, special grippers that hold a number of different tools are necessary. There are special grippers that can handle glass tubes and plate glass.

The creative design of different grippers allows robots to perform many different tasks. Photo 10 shows a simple general-purpose gripper used on the Unimate 2000 series robot. Aside from picking up objects, the end effector may be a special-purpose tool, such as the welding torch shown in photo 11 or the high speed cutting tool shown in photo 12.

As mentioned earlier, it is desirable to have a number of articulations at the wrist so that the end effector can be positioned correctly. Photo 13 shows an end effector that has a deburring tool as well as a proximity sensor and a microswitch, both of which are used to sense the position of the workpiece. In this example, only two wrist articulations are need-

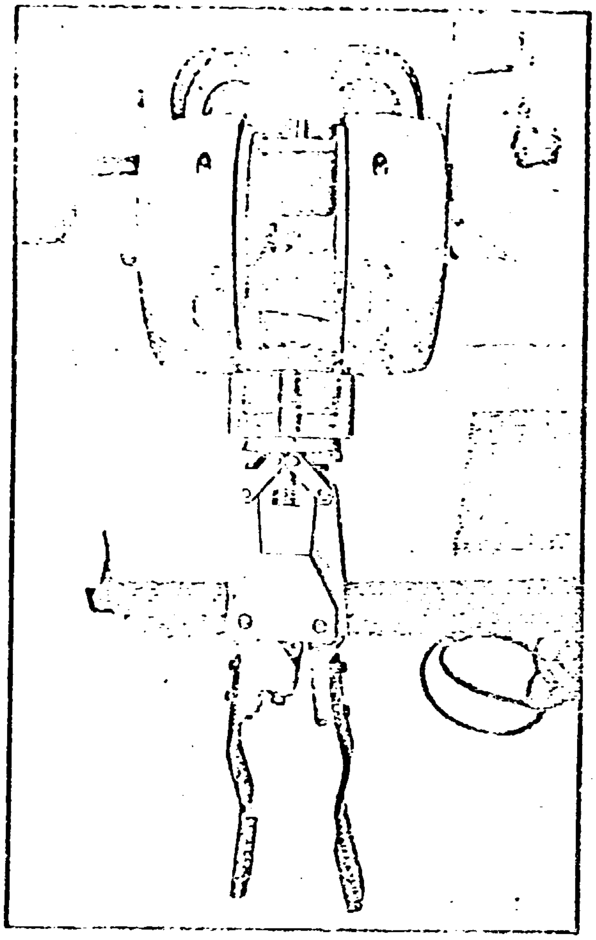

Photo 10: *General-purpose gripper used by the Unimate series 2000 robot.*

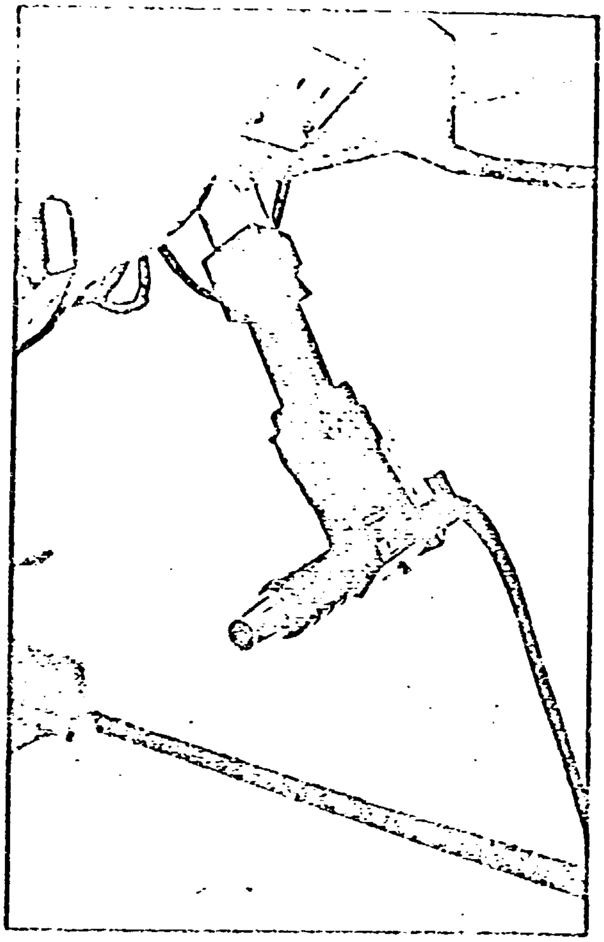

Photo 11: *The end effector on a robot does not necessarily have to be a grasping tool, as illustrated here by this arc-welding tool.*

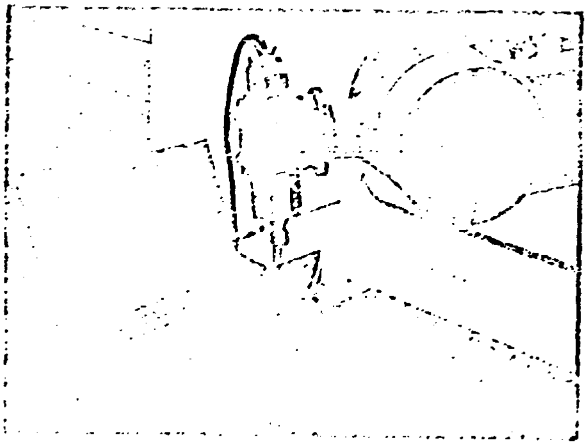

Photo 12: *A high-pressure cutting tool, used to cut plastic and fiberglass into [illegible] shapes, is shown attached to the end of an ASEA robot.*

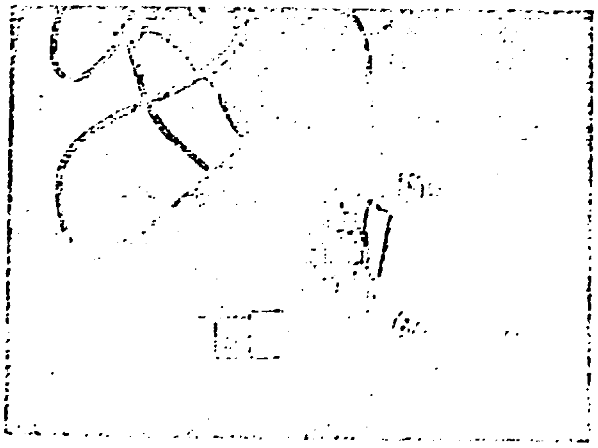

Photo 13: *A multifunction end effector with a deburring tool, proximity detector, and microswitch. The unit is moved around to place either the deburring tool or sensor against the workpiece.*

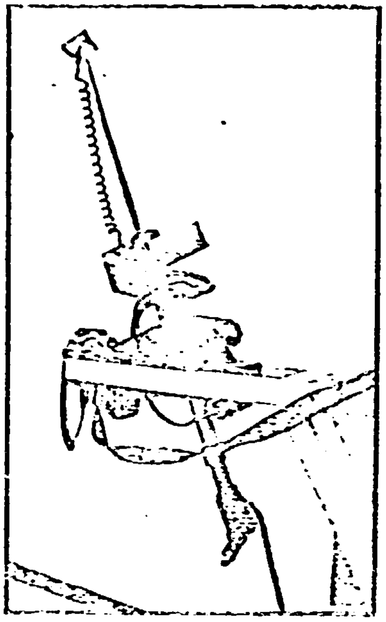

Photo 14: *The Unimation Apprentice is an example of a special-purpose robot designed to meet the demanding requirements of arc welding.*

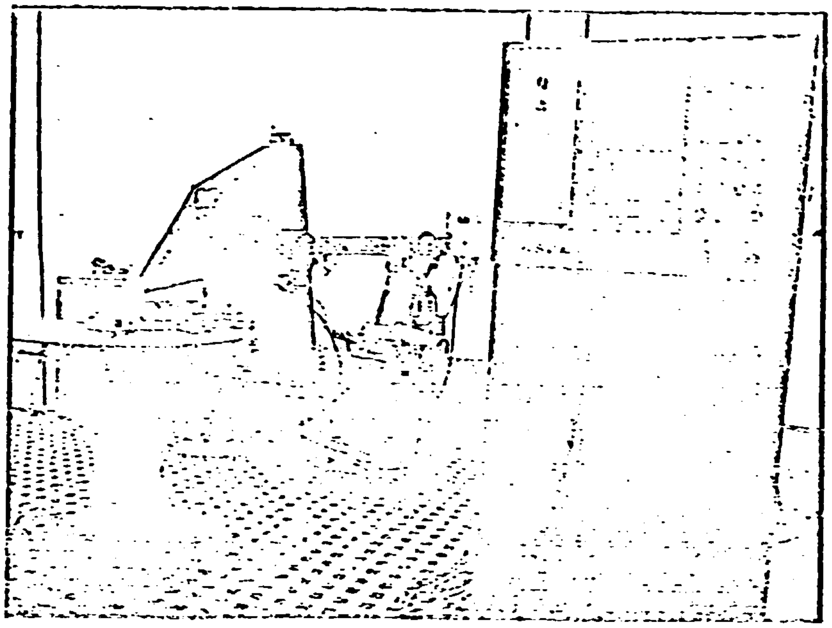

Photo 15: *An ASEA model IRb-6 is a scaled-down model of the larger ASEA robot. It has a lifting capacity of 13 pounds and position accuracy of 0.008 inch.*

Specifications for Seven Industrial Robots

	Unimation					ASEA	
	Apprentice	Puma 250	Puma 600	Unimate 2000B	Unimate 4000B	IRb-6	IRb-60
Number of degrees of freedom	5	6	6	3 to 5	3 to 6	5 to 6	5 to 6
Repeatability (inches)	0.040	0.002	0.004	0.050	0.080	0.008	0.016
Load capacity (pounds)	10	2	5	300	450	13	132
Programming capacity (no. of points)	N/A	N/A	N/A	2048	2048	15,000	15,000
Power required (kilowatts)	1.0	0.5	1.5	11.0	34.0	2.0	7.0
Cost ($ x 1000)	39	50	54	55	83	75	95

Table 1: *Representative sample of industrial robots available on the market today. Note the range of cost and capacities; this gives designers leeway to produce robotic systems for a wide variety of purposes.*

ed for the task. It is possible to move the end effector around the workpiece to put either the tool or the sensors in position by bending the wrist joint then exercising a yaw motion.

Systems and Applications

Up to this point, I have been discussing the components of industrial robots. Now I would like to talk about systems that are available and how they compare to each other. Performance measurements used to compare robots are position, repeatability, number of degrees of freedom, power requirements, maximum-lifting capacity, number of control options, and, of course, cost. Table 1, which outlines the specifications for seven different robots, presents a representative sample of what is available on the market.

Photo 14 shows the Unimation Apprentice robot, which is relatively small and easily movable. It was designed for on-site arc welding in confined spaces (such as the rib sections of a ship hull). ASEA also sells a small electric-driven robot (see photo 15). The conclusion I draw from table 1 is that a large number of different systems are available and a designer has a lot of flexibility in choosing a system.

Table 2 gives a breakdown of the five major industrial applications for robots. The die casting industry was the first to apply industrial robots. A robot can load a die-casting machine, quench the part, and trim off excess

Photo 16: *The Apprentice robot in action, welding a steel structure.*

Spot Welding	Tool Loading	Foundry	Spray Painting	Assembly Line	Other
35%	20%	15%	15%	10%	5%

Table 2: *The five major modern applications for robots. As the science progresses, robots will be used for a variety of industrial purposes, so the percentage of "other" uses will become larger.*

material. Robots are especially suited for die casting because of the harsh environment that exists in a foundry.

Welding is another area where robots have been used extensively. Photo 16 shows a Unimation Apprentice arc welding. Good arc welding requires close control of the welding gun along the weld path. It is essential that both position and speed are controlled to obtain a uniform weld with no unnecessary metal buildup or blowholes. Robots provide the position and speed accuracy needed in arc welding as well as in spray painting. For spray painting, it is important that the robot be able to follow a predefined path in order to obtain a uniform coat of paint. For details of robot applications, see references 4 and 5.

The Future

All of the examples here are of robots that can follow only a specific set of instructions. They are not capable of receiving information about their surroundings and adapting to changing conditions. In the next five years, advances will be made in the areas of sensor technology and the application of intelligence to robotic systems, giving a robot the capability to respond to a variety of environmental situations. Specifically, advances in vision and artificial intelligence will allow robots to become more adaptable.

At General Motors Research Laboratories, work is being done on a vision-based robot system that can recognize and pick up different-shaped objects moving on a conveyor belt. Advances in sensor technology will make proximity and tactile sensors commonplace on robots.

Another issue that must be dealt with in the near future is the standardization of robotic subsystems. Standardization should not limit new and innovative design but should allow for a common means of interfacing robots to computer-aided design/computer-aided manufacturing systems. We will certainly see advances in robot-control languages, such as VAL, in the near future. ■

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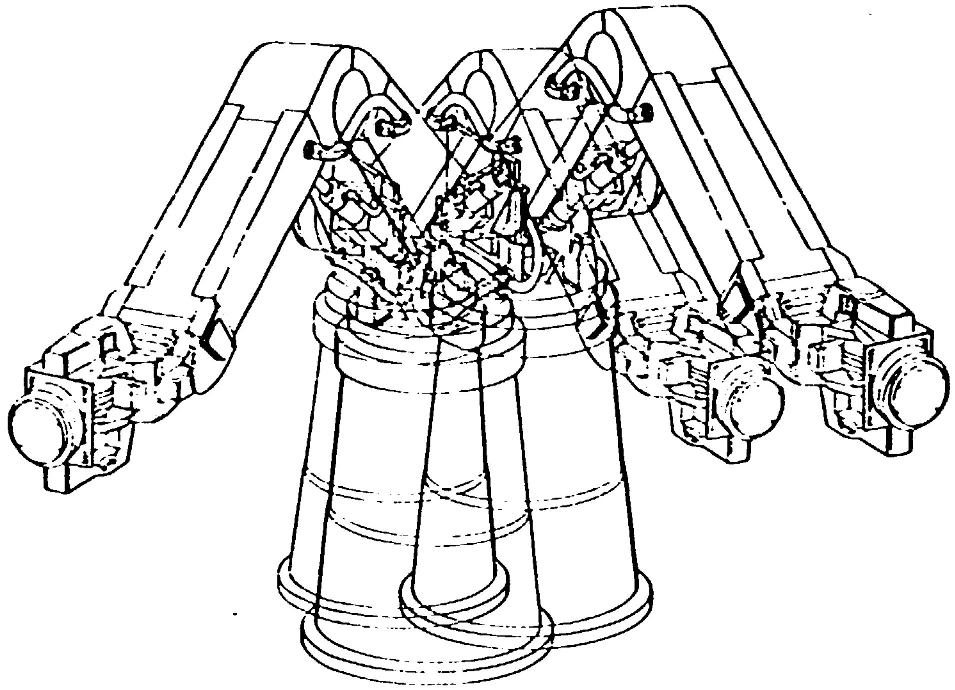

Computer Control of Robotic Manipulators

First, a review of the various classes of kinematic control — then, a look at the evolution of programming languages

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Rolla, Mo.

A robotic manipulator may be defined as a multidegree of freedom open-loop chain of mechanical linkages and joints. It is designed to perform mechanical operations which normally require the manipulative skills of humans. These mechanisms, driven by actuators, are capable of moving an object from initial to final locations or along prescribed trajectories.

Basically a robot consists of three components: the power supply, the mechanical unit, and the controller. The controller has a threefold function; first, to initiate and terminate motions of the manipulator in a desired sequence and at desired points; second, to store position and sequence data in memory; and third, to interface with external devices. Robot controllers can be step sequencers, pneumatic logic systems, diode matrix boards, electronic sequencers, microprocessors, or minicomputers. The complexity of the control determines the capabilities of the robot.

Nonservo-Controlled Robots

From the point of view of control, robots can be divided into two main types: nonservo-controlled robots and servo-controlled robots. Nonservo-controlled robots move their arms in an open-loop fashion between exact end positions on each axis, or along predetermined trajectories in accordance with fixed sequences.

Sequence Control. Motions of a nonservo robot are limited by mechanically adjustable hardstops on each mechanical joint or axis. Each axis can therefore move in an open-loop fashion to only two positions. A sequence control uses stepping switches or pneumatic logic sequencers capable of executing single problems of about 24 consecutive steps, or electronic programmable controllers with greater program capacity. In addition to initiating the motions of the manipulator, these controls also transmit and receive signals to and from other equipment with which the robot operates.

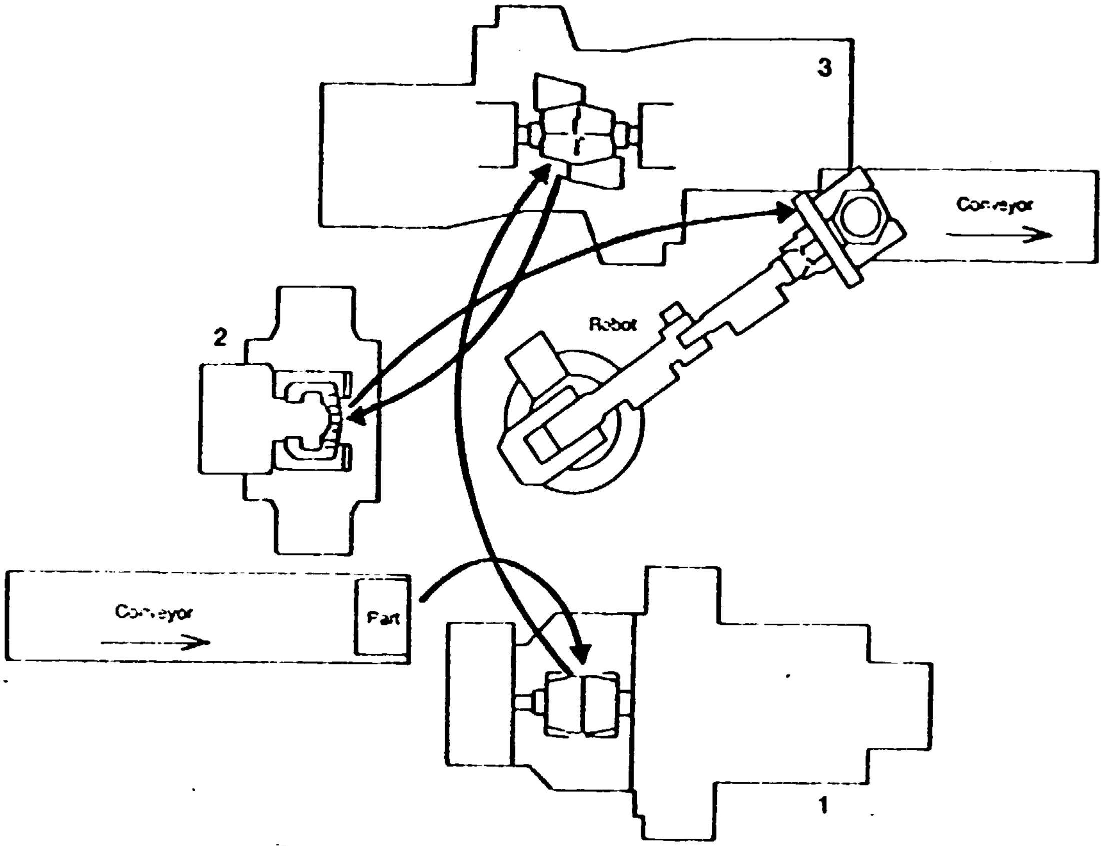


Fig. 1 Point-to-point control in heavy parts transfer operation. (1) Turning station, (2) Drilling station, (3) Threading station.

Limit-Switch Control. In a limit-switch-controlled robot more than one position can be defined along an axis by indexable stops inserted or withdrawn automatically. A sequence type control steps through a number of preset logic steps, which causes one or more joints to move until the appropriate limit switch on the axis is reached.

Servo-Controlled Robots

Servo-controlled robots incorporate feedback devices on the joints or actuators of the manipulator which continuously measure the position of each axis. This permits the control to stop each axis of the manipulator at any point within its total range, rather than at only two, or a few points. Servo-controlled robots have much more manipulative capability than nonservo robots by being able to position a tool or gripper anywhere within the total work envelope. The controllers in servo robots may be electronic sequencers, minicomputer- or microprocessor-based control systems. This class of control systems has magnetic or solid-state electronic memory devices for storing a taught sequence of motions in digital form.

Point-to-point (PTP) Control. In point-to-point control each joint is controlled by an independent position servo with all joints moving from position to position independently. A typical configuration for point-to-point motion in machine loading operations is shown in Fig. 1.

Teaching a robot for point-to-point motion is done by moving each joint (or axis) of the robot individually until the combination of joint positions yields the desired position of the end effector. When this position is reached, the position of each joint is stored in a memory device. In replaying the stored points, each joint freely runs at its maximum or limited rate until it reaches its final position. There are three ways of controlling point-to point motion independently: 1. sequential joint control (PTS-S); 2.

uncoordinated joint control (PTP-U); and 3. terminally coordinated joint control (PTP-T).

Sequential Joint (PTS-S) Control. Sequential joint operation is the activation of one joint at a time, while all other axes are immobilized. A single joint may operate more than once in a sequence associated with such a motion. The resulting path of the manipulator end effector will have a zig-zag form associated with the motion directions of the manipulator joints. Sequential joint control results in immediate simplifications in the control of an industrial robot. However, sequential control causes longer point-to-point motion times. This type of control will be helpful for highly modularized programmable assemblers where individual joints could be easily arranged into multijoint manipulators.

Uncoordinated Joint (PTP-U) Control. In this mode, the motions are not coordinated, in the sense that if one joint has made some fraction of its motion it does not imply that all other joints will have made the same fractions of their respective motions. When each joint reaches its final position it holds and waits until all the joints have completed their motions. Since there is no coordination of motion between joints, the path and velocity of the end effector between points is not easily predicted.

Terminally Coordinated (PTP-T) Joint Control. This is the most useful type of point-to-point control. The individual joint motions are coordinated so that all joints attain their final positions simultaneously. It is used primarily in applications where only the final position is of interest and the path is not a prime consideration.

Continuous Path Control

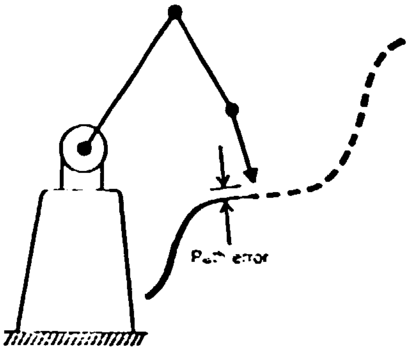
This type of control is used where continuous path of the end effector is of primary importance to the application. Continuous path motions are produced by interpolating each joint control variable from its initial value to its desired final value. Each joint is moved the minimum amount required to achieve the desired final positions to give the robot tool a controlled predictable path. All the joint variables are interpolated to make the joints complete their motions simultaneously, thus giving a coordinated joint motion.

Continuous path control techniques can be divided into three basic categories, based on how much information about the path is used in the motor control calculations. These are illustrated in Fig. 2.

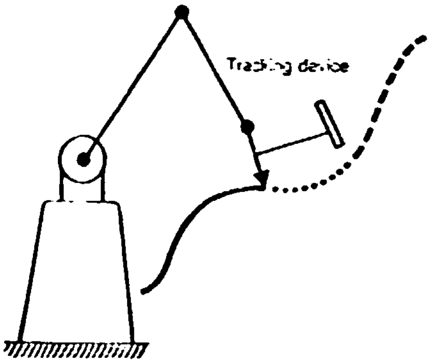
The first is the conventional, or servo control, approach. This method uses no information about where the path goes in the future. The controller may have a stored representation of the path it is to follow, but for determining the drive signals to the robot's motors, all calculations are based on the past and present path tracking error. This is the control design used in most of today's industrial robots and process control systems.

The second approach is called preview control, also known as "feed-forward" control, since it uses some knowledge about how the path changes immediately ahead of the robot's current location, in addition to the past and present tracking error used by the servo controller.

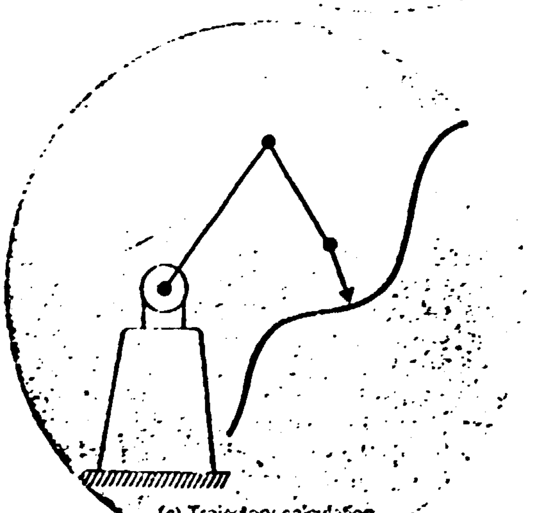
The last category of path control is the "path planning" or "trajectory calculation" approach. Here the controller has available a complete description of the path the manipulator should follow from one point to another. Using



(a) Basic servo control



(b) Preview control



(c) Trajectory calculation

Key:

↓ Present robot position

—— Known path

.... Path measured in real time

– – – – Unknown path

Fig. 2 Three categories of continuous path control.

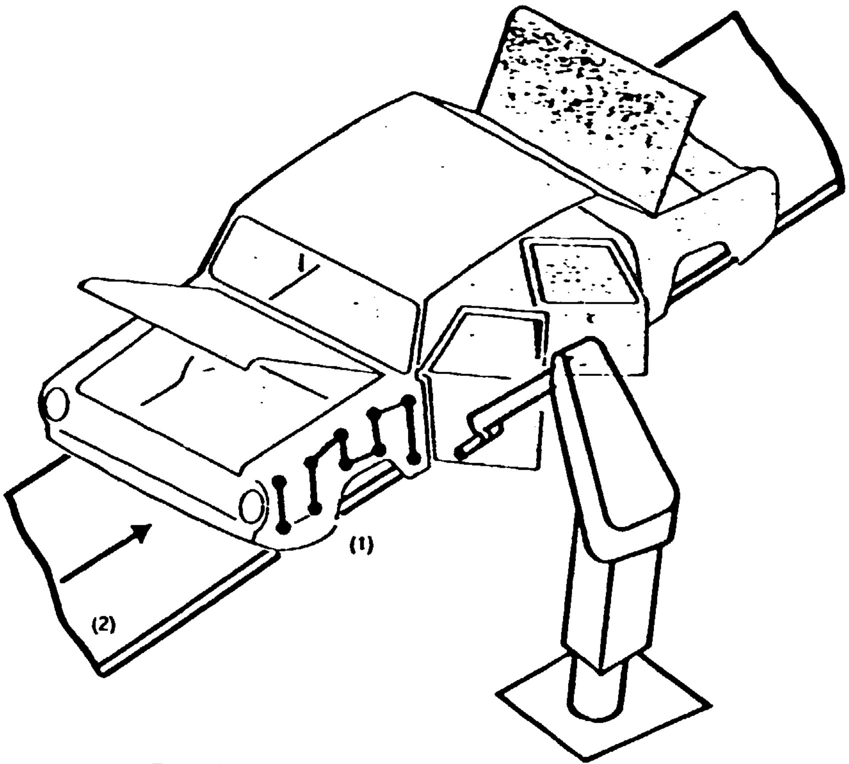
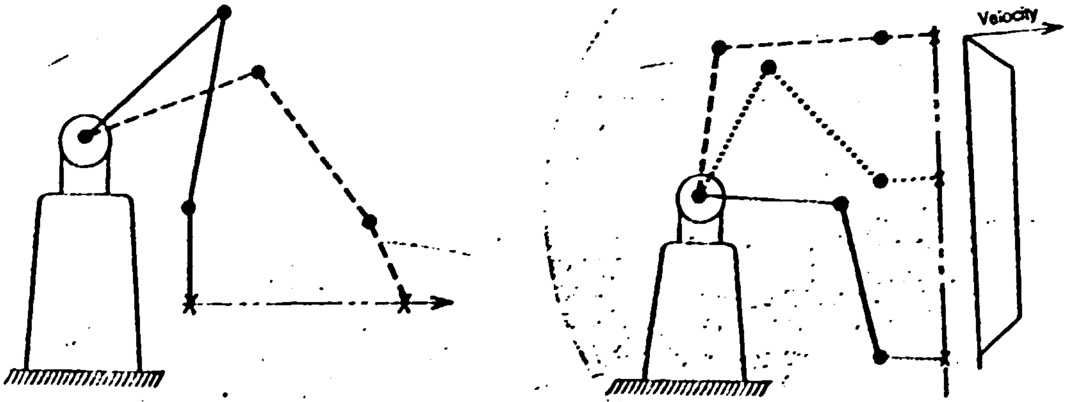


Fig. 3 Synchronization of continuous path with a moving conveyor. (1) Instructed paint path, (2) Moving conveyor.



(a) Path control with orientation change

(b) Straight line path generation with controlled velocity

Fig. 4 Cartesian coordinate control.

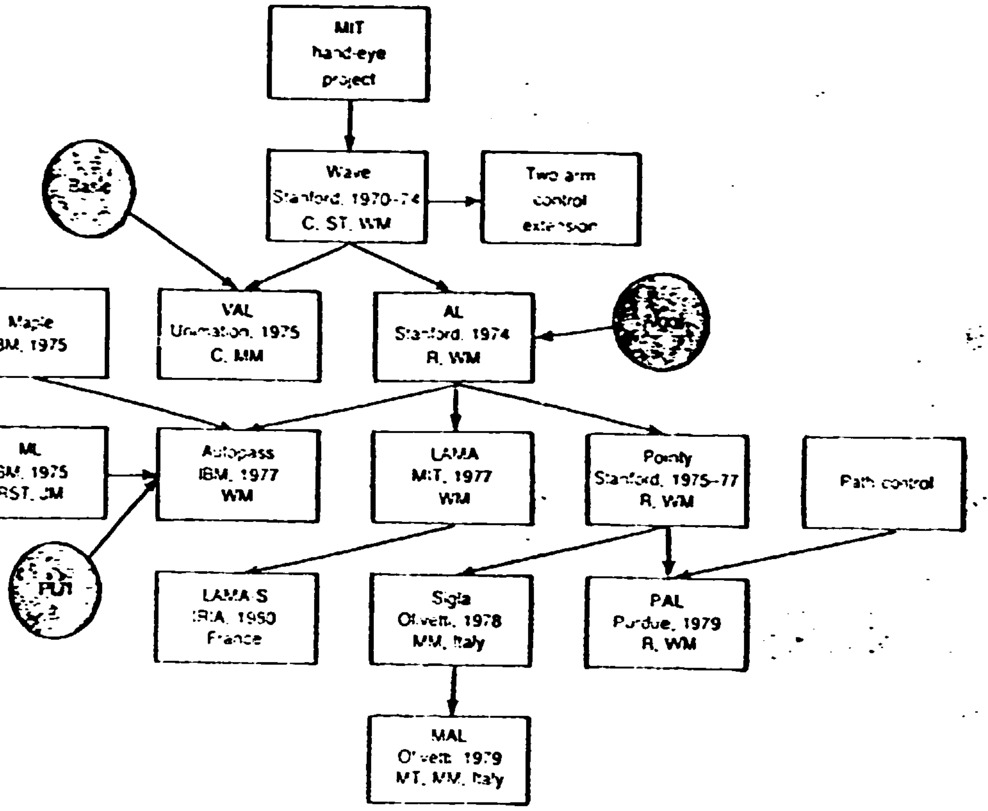


Fig. 5 Robot programming languages evolution and classification.

a mathematical-physical "model" of the arm and its load, it precomputes an acceleration profile for every joint, predicting the nominal motor signals that should cause the arm to follow the desired path. This approach has been used in some advanced research robots to achieve highly accurate coordinated movements at a high speed.

Typically, robots using continuous path control are taught by the operator physically grasping the unit and leading it through the desired path in the exact manner and speed the robot is to repeat the motion. While the device is moved through the desired path, the position of each axis is recorded on a constant time base, thus generating a continuous time history of each axis position. Every motion that the operator makes, whether intentional or not, will be recorded and played back in the same manner. Since the operator must physically grasp the robot, it must be designed to be essentially counterbalanced and free, so that the task can be performed. Therefore this control is generally limited to light-duty robots. Since the operator is manually leading the robot through the desired sequence, the teaching is instinctive and there is no concern for the position of each axis. Another characteristic of this type of control is that considerable memory capability is required to store all the axis positions needed to smoothly record the desired path. For this reason, magnetic tape and disk storage means are generally used.

Cartesian Motion Control

In cartesian motion generation, the locations are expressed in terms of the cartesian coordinates (x, y, z) and orientation angles of the robot tool relative to a reference frame (world coordinate system) fixed in the base of the robot. The use of transformations is especially advantageous where relative translations and rotations are to be performed. However, the use of cartesian coordinates to define locations can be at times somewhat inaccurate due to the complexity of the computations necessary to convert between the cartesian coordinates and joint angles via homogeneous transformations.

Cartesian motions are generated by applying an interpolating function to the cartesian location of the manipulator's tool tip and rapidly transforming the interpolated tool tip location to joint commands. The path is prescribed in rectangular space and requires that the kinematic equations of motion be solved in real time to continuously output to the axis servos. Figure 3 shows the path of the tool center point (TCP) for a typical move, in which the path is along a straight line even though the orientation has changed linearly along the path. The velocity profile for a cartesian motion, with an acceleration span at the beginning and a deceleration span at the end of the path, is also shown.

When teaching such a system, the computer solves the equations of motion so that the axes are coordinated to give the desired motion, such as straight up in the z coordinate direction, or left in the x coordinate direction. The operator thinks only in terms of the desired motion of the end effector, not the motion required at the axes. Similarly, the operator can change the orientation of the end effector about a point without changing the position of the point, or independently change position or orientation of the end effector relative to the TCP.

Cartesian motion control is useful in full tracking applications requiring synchronization with a moving conveyor using a stationary base robot, as in Fig. 4. In the elementary form of stationary base tracking, the robot is taught the task while the conveyor or part is in motion. During replay of the taught program, the speed of replay and the speed of robot motion are synchronized with the line. While this type of tracking system is satisfactory for point-to-point tasks, continuous path tasks requiring the TCP to maintain the same velocity relative to the part as when taught, cannot use this system unless the conveyor speed is constant without interruption in its motion. For example, when automotive assembly-line spray painting, if the conveyor stops, the robot cannot stop but must continue to move at the same velocity relative to the part. For cases where constant uninterrupted conveyor speed cannot be ensured, "full tracking" capability is required. The net effect of this capability is to perform the task, relative to the part, independent of conveyor motion.

Coordinate Model Classification

Servo-controlled robots are nearly always computer controlled and "programmed" in a procedural language which may vary considerably in complexity, depending on the flexibility of the robot. Robot programming languages may be divided into three categories, according to the focus of the programmer.

At the lowest level are the Joint Model languages. Here the programmer's attention is focused on the control of individual joints, actuators, and sensors. ML, as well as most nonservo-controlled robot command languages, could be placed in this category.

Most commercially available robot languages are in the category of Manipulator Model languages. Here the programmer's attention is focused at the end effector or manipulator tool tip, and the task is to guide the tip from point to point through cartesian-coordinate space. Languages in this category include Unimation's VAL, Olivetti's Sigla, Bendix's Teach, and Phillips' INDA as well as several well-known languages in the research community such as MIT's WAVE.

The third category of robot languages are the World Model languages. Here the programmer's job is more goal directed. End effector motion is described in terms of the position and motion of the objects being manipulated. Thus the programming can largely be done off-line in terms of a preestablished data base describing the parts to be assembled, or objects to be manipulated. This concept is more in line with an integrated CAD/CAM approach than the first two categories. Languages in this category include IBM's Autopass, Stanford's AL and LAMA, Purdue's PAL, and the University of Edinburgh's RAPT.

Classification of Robot Language

Robot Language	Commercial	Research	Single-task	Multitask	Joint model	Manipulator model	World model
Wave		•	•			•	
VAL	•					•	
AL		•					•
ML		•	•		•		
Autopass							•
Pointy		•					•
Sigla						•	
MAL				•		•	
PAL		•					•
LAMA							•
LM		•				•	
Robex		•				•	
Inda	•		•			•	
Teach	•					•	
Help	•					•	
Rail	•		•			•	

Language Evolution

Figure 5 shows a sampling of some existing robot programming languages. They have been categorized according to the previous models, as well as whether they are used commercially or in a research environment (see Table). As might be expected, the commercial languages tend to be the more straightforward and conservative Manipulator Model types, whereas most research interest is in the World Model category. Where it was available, evolutionary history and the influence existing high-level languages have had on robot programming, has been included.

Summary information for each language includes the name (e.g., VAL), date it first appears in the literature (e.g., 1975), developing organization (e.g., Unimation), and whether it is intended mainly for commercial (C) or research (R) use, whether it is considered a single task (ST) or multitask (MT) language, and the type of coordinate model on which the language is based (WM world model, MM -manipulator model, JM -joint model).

Based on a paper contributed by the ASME Computer Engineering Division

Computer Aided Manufacturing— A Stepping Stone to the Automated Factory

Although the automated factory seems to be just around the corner, it may be quite some walk to reach that corner. And even though a number of large manufacturing companies are getting close to it, it still isn't the real thing. Maybe a lot more has already been done than is generally realized.

NIKITA ANDREIEV, CONTROL ENGINEERING

Automatic factory is like a cake in the making. The flour, the eggs, the raisins, sugar, spices, and all other ingredients are there, but the cake isn't ready. You need to add something to make it a whole, to bind it together—dough and baking. The plain fact is that there is no such thing yet as a completely automated factory. Today, only separate pieces exist, in various stages of development and implementation, of a system that is often referred to as the automatic factory of the future. Also, if you had the means to commission an automated factory today, you would discover that no single manufacturer makes all of the components. Thus, you might go to H-P for a factory floor reporting system, to Calma for software, to Westinghouse for something else, and so on down the line. And provided you get all the components under one roof, you are faced with a problem before which even the builders of the Tower of Babel stumbled.

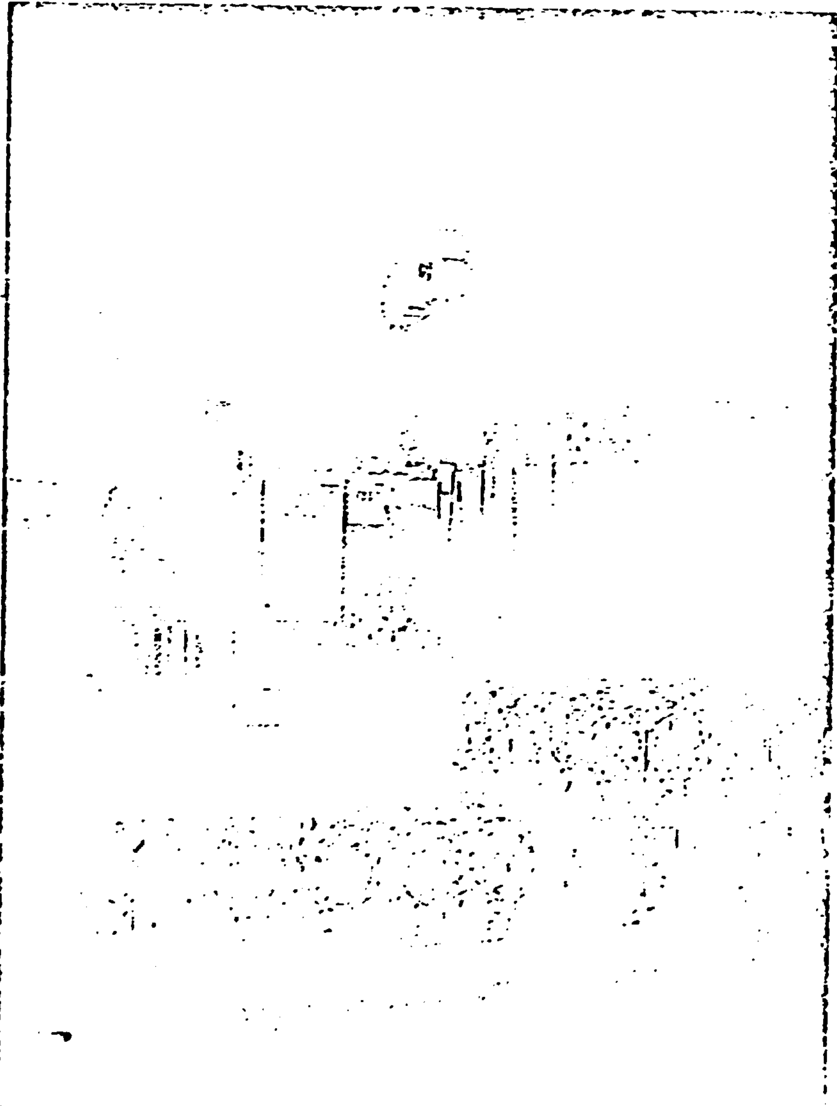
Communications—the glue

One of the ingredients, believed crucial to automatic factory success, that is missing today is a unified intraplant communications link. Without communications you cannot even start talking about that factory. Currently, the communications or the data highway is being tackled by a number of manufacturers, and the race is on to be the first one to produce a winner good enough to become a standard. A related task, that of standardization, is in the hands of the National Bureau of Standards. Its product, the IGES (Initial Graphics Exchange Standard) will permit transportability of geometric modeling software among many commercially available CAD-CAM systems. CAM-i, in its turn, recently covered the subject of designing processors at the 10th Annual Meeting and CAD-CAM Graphics Users in Fort Worth, TX. Lack of a unified communications standard and the fact that each manufacturer has its own protocol is a strong incentive to push a quick solution.

Expensive alternatives

The alternative, and problems, of tying together systems from many sources, each speaking its own language, is well documented at Boeing. Faced with the gargantuan task of implementing a plant-wide CAD-CAM network, Boeing decided to solve the communications problem by creating a translator. That device would then enable the already existing components such as IBM computers to talk to Applicon's CAD system, which would talk to Computervision's system, and so on.

The project was eventually completed but the catch was that it took Boeing several years to complete it, and the government helped in footing the bill. Anybody smaller than this aerospace giant probably doesn't have the resources to undertake such a task.



Valtek's NC machining center features a tape controlled Matsuura milling machine used to finish process valve bodies seen in the foreground. Note the flexible manufacturing elements in the quick-change tool mechanism at top

In addition to the communications aspect, there are other causes contributing to delays in CAM projects. Thus some manufacturers' attitudes and stubborn unfamiliarity of potential users with the new technology are but some. Consider for example, the fact that many manufacturers of control systems see themselves neither as control systems manufacturers nor as part of a larger picture. Consequently, they are designed in rather parochial, narrow and [illegible] views.

Resistance to CAM is strong

Recently, a West Coast ATE (Automatic Test Equipment) manufacturer that makes a complete computer-based test system that includes provisions for automatic loading and unloading of component units under test, was totally disinterested in what was going on outside of the test department. "Once the component leaves the test area, it's somebody else's problem," was a typical answer. As a result the system, even though quite sophisticated technically, was quite limited when viewed against the background of the total manufacturing picture. The system could report to a remote computer minute to minute information, but there was no provision, nor was one planned in the future, to enable the computer to control the testing in response to some outside influence such as overstocked shipping room. Such "me only" attitudes are not unique in industry.

Also, there seems to be a third factor, rather intangible, that may inhibit faster implementation of CAD-CAM and that is an inability of some sectors of industry to absorb and believe in the possibility of such systems. Texas based CAM-i, a non-profit organization interested in dissemination of CAD-CAM technology to a broad audience, recently reported that a well known educational institution solicited advice that would help it obtain a grant to study possible application of computers to manufacturing and management. The same CAM-i source couldn't envision such happening in view of the large volume of information on CAD-CAM systems presented in virtually every periodical today unless the 'ivory tower' syndrome was responsible. And the case just mentioned is not an isolated phenomenon, which indicates a need for broader education.

And education through information dissemination is what CONTROL ENGINEERING [illegible] planning [illegible] [illegible] with Purdue University. CONTROL ENGINEERING is putting together a technical conference that will address the subject of computer aided on-line production scheduling and plant wide control. To find out more about this conference, its sponsors, read our in-house ad on page 157 of this issue.

Many large companies have had good success with automated factory components. The achievements of Hewlett-Packard in computerizing its printed circuit board manufacturing facility in Sunnyvale, or John Deere's Waterloo, IA tractor assembly plant, or IBM's silicon wafer processing plant in Essex Junction, VT have been well publicized. Not to mention Big Three's automotive assembly plants in and around Motor City.

The goal in all cases is to assure survival in the new economic climate that is shaking to the foundations the old concepts of manufacturing and control. And while old concepts are crumbling, computer-aided manufacturing techniques help increase productivity, improve and then maintain product quality, reduce paperwork, and in general, improve the efficiency of labor intensive management and manufacturing processes.

But until recently there has been no record of a small to medium sized company being able to benefit from these developments in the same manner as do the big companies. The reason? Cost, mostly, but lack of experience with computer-based equipment could be a close second. The huge investment required to enter CAD-CAM has discouraged all but the largest manufacturers. And even then, particularly among the aerospace companies, much of the initial cost was borne by the government. Thus, CAE (Computer Aided Engineering) remained in the realm of the leviathans until the hardware prices started coming down and the basic software to drive this hardware had been developed and paid for. Even today the government continues to be active in a number of projects. For example the Air Force sponsors ICAM (Integrated Computer Aided Manufacturing) project, whose objective is to "...achieve major increases in productivity in aerospace batch manufacturing by widespread application of computer based methods for fully integrated factory management and operation."

Things are changing, however. And the fact that the smaller guys are getting in at the bottom of the ladder is an encouraging sign. For one it indicates that the price of system components is getting lower and the productivity gains are substantial enough to encourage investment in these systems. For example, Aydin Controls is about to announce a turnkey CAD-CAM system that will sell at a fraction of the price of an equivalent system today. The system was designed from the [illegible] microprocessor [illegible]. Most of today's systems [illegible] puter based.

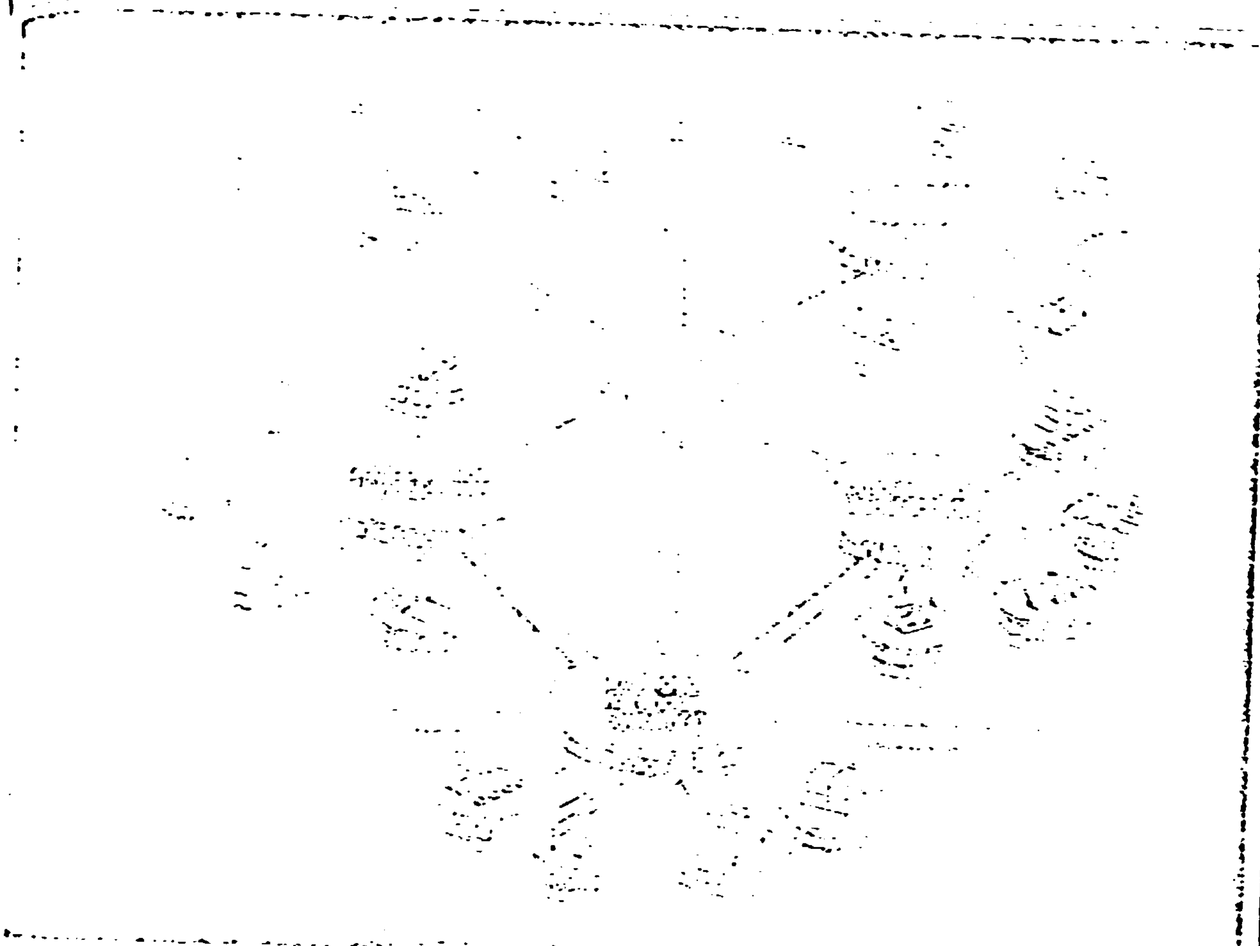
"We are at the threshold of [illegible] plosion. The current state of the art [illegible] CAM is in discrete parts manufacturing [illegible]. The key fact is that it is [illegible] viable tool not only for Boeings, GMs and IBMs, but also for the small [illegible]," says Dr. Pat Hanratty, president of [illegible] vine-based MCS. Dr. Hanratty is talking about NC tape making.

About the only serious [illegible] into CAM are in NC techniques for tape generation directly from engineering drawings. Some, like Hanratty, believe that in the near future that is what it [illegible] will essentially be. Small companies, staffed with industry-oriented programmers, who often have extensive manufacturing process experience, and who are not intimidated by the computer, provide a service to the industry – in other words small job shop operations.

It is interesting to note that according to a GE study the human programmer will be in the loop for many years to come. "We can only improve the man's productivity but we cannot yet eliminate him. His knowledge of machine tooling and process is still needed. In other awords, CAD is making the process more efficient but the human knowledge will be needed for a long time. Looking at it in another way, we can shorten what he is doing, by increasing greatly his productivity," says GE's GEISCO (Rockville, MD) manager of CAE marketing Dave Bruce, "but we cannot replace him with a computer. Not yet, anyway."

The same GE study indicates that a company that uses computer assist to do its NC tapes may experience up to four-to-one improvement in programmer productivity. "Using conventional, computer-assisted methods to prepare NC tapes, a programmer may spend 20 percent of his time selecting tooling, 40 to 50 percent defining geometry, another 20 percent defining motion statements, and the rest debugging," says Dave Bruce. "Contrast this with graphics aided situation where programming time can be reduced about 50 percent, mostly in the defining geometry slot which is now automated by the CAD system. The new breakdown includes 30 percent for tool selection, 30 percent for defining geometry, 30 percent for additional information on tool motion, and the remaining 10 percent for debugging."

A company exploiting a CAD-CAM system is Valtek (Springville, UT), a process valve manufacturer. It originally purchased the system from Gerber Scientific to i[illegible] the efficiency of



• FIG. [illegible] 's "A Road Map to the Factory with a Future" are gathered [illegible] components of today's manufacturing function [illegible] in the above diagram that both the rims and the hubs exist today. What is missing are the spokes

drafting function. The phenomenal [illegible]cess of the venture (see pps. 51- [illegible] Feb. 82 CF) encouraged the com[illegible] to take the next step—CAM.

[illegible] for a small manufacturer the path [illegible] When Valtek, a medium-sized [illegible] (less than 500 employees), [illegible] to purchase a CAD-CAM system it [illegible] into a snag with the system manu[illegible]. It seems that the system man[illegible]turer was concerned, and with [illegible] reason, about the success of the [illegible]avor. With no precedent to go on, [illegible] manufacturer was worried that in [illegible] of a failure to implement the sys[illegible] successfully, the disaster could [illegible] an unfavorable light on its other[illegible] excellent reputation. And you [illegible]n't blame them. One of the prob[illegible] was that these pioneers had no [illegible] trail to follow, hence it [illegible] that were expected to [illegible] path. About 30 percent of in[illegible] CAD-CAM systems fail, accord[illegible] [illegible] Corp., because of [illegible]

[illegible], Valtek has been ex[illegible], and following the [illegible] period it has com[illegible]pleted the CAD portion of the project, and is well on the way to implementing CAM.

Another successfull pioneer is Graphics Manufacturing Systems, Inc. (Santa Ana, CA), a small owner service organization for NC machine shops. The company specializes in making NC tapes for intricate shapes that are difficult to describe on a drawing. Examples of such shapes vary from turbine blades to crane hooks to machine tool forgings. Its president, Ed Bell says: "We are successful because all of our programmers came from the industry. They are intimately familiar with shop floor procedures, manufacturing processes, even the peculiar habits of the people working in these surroundings. Thus the tapes the company makes are done by the experts. To make sure the tapes are good, we run a test pattern at an NC machines [illegible] facility to which we have access." The company has recently installed a [illegible] computer to do all the number crunching.

Still another story comes from a small job shop, National Carbide Die (McKeesport, PA), which in the past contracted for NC tape writing services companies such as GMS, but recently decided to do its tapes in-house. The company supplies precision tools and dies to companies that manufacture powdered metal and ceramic parts to automotive, electronic, and other industries. Most of the time the dies are one of a kind, and in the past, investment in NC machinery was impractical. Today, however, the availability of turnkey CAD-CAM systems as well as special software that requires only a minimum of programming makes such investment commercially viable. Thus, NCD built its own system consisting of an HP 9835A desktop computer, plotter, printer, disk memory, and tape punch, bought interactive software from Milwaukee-based [illegible] N/C Systems, and proceeded merrily to make money manufacturing dies. For example, to make a program for an NC machine, the programmer, using the [illegible] software, keys in [illegible] data and other information directly from an engineering drawing. The [illegible] [illegible] software is particularly useful [illegible] generating [illegible] for various gear designs.

Most components are ready

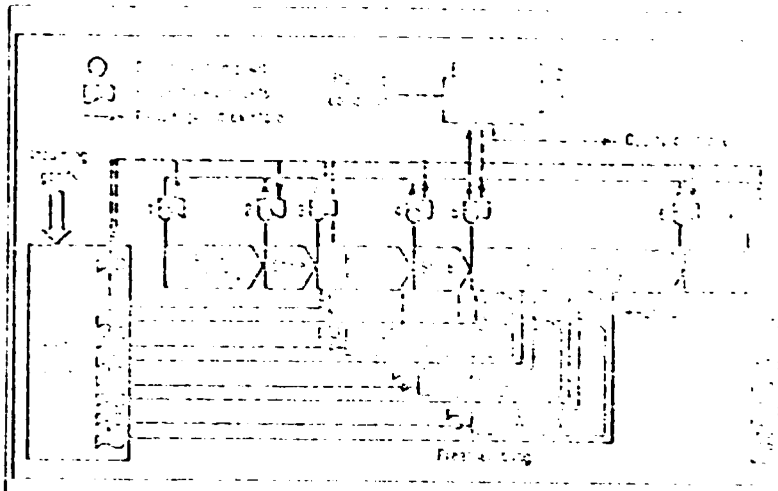
But fortunately, to most in the industry the subject is not new, the confusion usually arises in tracking who does what. To see which portions of the automated factory are available today, let us refer to a typical manufacturing facility [illegible] by General Electric and reproduced on page 55.

Starting with the operations management system at the upper left, notice that items such as order entry, purchasing, and so on around the circle, have been computerized for a number of years. Not shown on the diagram is the entire financial side of a company which includes payroll, billing, and other functions customarily referred to as electronic data processing (EDP).

A shop floor control system has been recently installed by H-P at its facility in Grenoble, France. The system uses H-P's components to log jobs, monitor production, assign operators, read badges, and in general perform complete control of work in progress. Another manufacturer, Burr-Brown (Tucson, AZ) is planning to install a similar system in its plants using HP 1000 computer for the data base but using its own portable terminals to enter and record shop data. Burr-Brown declined to give a figure that it expects to save by installing the system, but the cat-that-ate-the canary smile tells of the expectations. Notice the difference in sizes between the two manufacturers; the system works for both, and both claim that it is practical for a much smaller manufacturer.

Continuing clockwise around the hub of GE's diagram, you come across the CAE (computer-aided engineering) cluster. We skipped the spoke marked data with public or private networks, because the challenge of this topic has been mentioned before. The topic of CAD, which included the topic of analysis, was covered by CONTROL ENGINEERING in a February article. Next items like NC programming and mold design have been successfully computerized and have made the deepest penetration "downward".

The CAE area is also the most highly developed to the point that the software can be readily purchased from a number of sources. One such software product is Lockheed-developed CADAM (computer graphics augmented design and manufacturing) system that took 10 years to perfect. As the name suggests, this is an interactive, general purpose design and drafting system that contains analytical design aids for use in 3 dimensional design, drafting,



[illegible]'s computer optimizes this computer aided automated assembly line

NC part programming, and other engineering and manufacturing applications. The CADAM software unites the design and manufacturing through a common data base. The software can also be customized for applications in architecture, civil engineering, and facilities planning.

Two faces of CAM

Even though in the diagram CAM is broken up into manufacturing and test, and final assembly and test, this was done more for esthetic than functional reasons. Let's start with assembly robots—it's a topic whose ship has finally come—that resulted in a bumper crop of small high technology companies. Some, like Boston-based Automatix, are only a couple of years old but are already offering products with vision for welding applications.

Continuing around the loop with automated inspection and test, it has been an autonomous operation for a long time and all that it needs is hooking up to the rest of the plant. Programmable controls, of which the PC or programmable controller is the most widely known example, has been around for more than a decade and its applications were developed to a high degree by the automotive industry. Lately, the PC is fast penetrating other industries (see March '82 CONTROL ENGINEERING, page 52).

Jumping to the manufacturing side of CAM, you will notice the same picture. All of the components in that cluster are well known and working. Welding and painting robots have been proving themselves in and around Detroit for years. Material handling robots are of more recent origin, but a number of them, by Cincinnati Milacron, [illegible] installed in Cadillac's Livonia plant to handle forgings [illegible] ching operation.

Finally, the intelligent warehousing system has been recently successfully implemented by John Deere in its Waterloo, IA tractor assembly plant. Its effectiveness has been attested to by *The Wall Street Journal* in a recent analysis of the impact of current recession on John Deere's financial health. At one point the Journal, quoting Deere's chairman, said that in view of the company's moves to improve productivity [through computer aided manufacturing] even a modest recovery should produce substantial improvements in John Deere's earnings. Can a small guy achieve such success? Apparently the answer is yes. Veltek reported substantial productivity gains using CAD, and indicated that even more impressive gains will be achieved upon implementation of CAM.

Don't wait for tomorrow

But it takes more than the availability of components to push forward—it takes the right attitude. The fact that there is only a handful of components "of the future" available today doesn't faze Larry Dougherty of Gould's Factory Automation Division in Nashua, NH. "We have solutions to a set of problems," says Larry at a recent interview in Chicago. "And with those that are available we are in the business of trying to get the job done today." The division markets a factory monitoring and control system that communicates with its far flung intelligent devices via its own communications highway. "Bring the information up from the factory floor in a logical manner," continues Dougherty. "A well planned program will eventually allow you to [illegible] the ladder [of progress]. And the next step [illegible] (in the past the system was [illegible] only), [illegible] display the [illegible] throughout the factory floor." □

CAM Software Is Evolving From Closed Loop Manufacturing to Real-Time Control

[illegible] that [illegible] and [illegible] and [illegible] of all our [illegible] As more and more intelli- [illegible] computa- [illegible] industry, in al [illegible] this [illegible] through a funnel. But as the torrent of data the [illegible] turns into an [illegible] system can handle it all [illegible] yet.

The key [illegible] software [illegible] recently, there were dozens of service companies and software firms [illegible] took the [illegible] of them and [illegible] with over 120 engaged in [illegible] software [illegible] They still [illegible]

But [illegible] and some, [illegible] expertise to venture into the newly "discovered" [illegible] The software that started coming out is known as closed-loop manufacturing software systems (CLMS). This software [illegible] through [illegible] with inventory, planning, material re- [illegible]

[illegible] tailored to particular user require- ments. The system essentially pro- vides input, update, and retrieval and reporting of current manufacturing data. The company happens to supply [illegible] software for large system [illegible] computers [illegible] part for real-time plant control soft- ware which will eventually [illegible] the automated factory [illegible]

Change to software-driven systems

[illegible] being written [illegible] companies are currently [illegible] enough to be involved in its produc- tion), the buying habits of users may change by shifting the emphasis from hardware to software. And there is [illegible] happening in light of the [illegible] given to [illegible] software [illegible] will become the driving force [illegible] says [illegible] Group [illegible] Software [illegible] there will be a change [illegible] buying hardware [illegible] (they [illegible] all be very [illegible]) [illegible] the right software [illegible] IBM, HP, TI and others [illegible] software. They are [illegible] this [illegible] market [illegible] software."

"Today the automated factory [illegible]

[illegible] lator for [illegible] type of data, reformatting it, and sending it some- where else.

[illegible] expensive, still.

Standardization and integration

Thus basically, there are two prob- lems to be solved first before [illegible] automated factory [illegible] The first one is [illegible] data [illegible] The second one is [illegible] integration.

Lack of a standard [illegible] results in what [illegible] seem at first [illegible] but [illegible] turns out to be the only [illegible] way to go today with limited re- sources. Example [illegible] company that is [illegible] a shop floor reporting system and at the same time wants to [illegible] its manufacturing procedures. The shop floor reporting system is [illegible] company and the CAD/CAM equip- ment from an [illegible] The result? The company is going to [illegible] two sets of wires, one for each [illegible] reporting. And [illegible] even if the two systems that are [illegible] compatible must be [illegible] in such an expensive way. The [illegible] that both are available now.

And the [illegible] is not [illegible] since the current software and hard- ware language barriers are yet to be broken. Some progress has been made. For example, [illegible] automated factory [illegible] there.

[illegible]

Profitable Robotic Work Cells Result From Interconnecting the Islands of Automation

As factory automation concepts become more widely implemented, users are finding that many industrial applications are best automated by integrating one or more robots and several machine tools into "work cell" arrangements. Controlling the robots and the various machine tools as a unified system within the work cell is no small task. Differences in protocols, languages, and even electrical connections make this a challenge. When you're finished, you've created an expensive "island of automation." Profitability results when there's provision for the eventual connection to the rest of the plant, and sufficient flexibility to accommodate new tasks as they arise.

HENRY M. MORRIS, CONTROL ENGINEERING

Robotic work cells are clusters of one or more robots and several machine tools or transfer lines which are interconnected in such a way that they work together in unison. A robotic work cell contains all of the necessary accessory equipment to create a particular work environment. In one of the better known examples, a robotic work cell was established that met any or all of the following criteria as defined in the report "ICAM Robotics System for Aerospace Batch Manufacturing — Task A," written by the Materials Laboratory, U.S. Air Force, Wright Aeronautical Laboratories, Air Force Systems Command, (Wright Patterson Air Force Base, OH)

- The work cell must employ a currently available industrial robot
- The work cell must be capable of performing the necessary machining functions on a limited number of parts of sizes within predetermined limits
- One worker must be capable of operating the work cell with minimal skill requirements.
- Selection of operators (personnel) from the shop floor must be possible.
- Manual parts fabrication in the work cell must be feasible in case of system failure
- Compliant end effectors must be employed due to inherent inaccuracies of available robots.
- Part programming must be done on line
- Safety sensors must be installed for protection of personnel, equipment, and parts
- Consistent quality must be maintained on parts, with no rejects
- Productivity increases must be provided to make the system economical.
- Early implementation must be made for quickest payoff

In his paper "The Industrial Robot In Computer Aided Manufacturing," George Munson from the Unimation Div of Westinghouse Electric Corp (Danbury, CT), wrote, "Except for large scale automotive installations and in specific types of jobs such as die casting, most robotic applications can be classified as 'islands of automation.'"

Addressing this subject, Jim Baker, executive vice president and sector executive of the Technical Systems Sector, General Electric Co (Fairfield, CT), told attendees to the Executive Session of ProMat '85 (the Material Handling Forum, McCormick Place, Chicago, Feb 25, 1985), "You cannot just design an automation process to make a product, you must also design the product so it can be efficiently made with automation techniques. If you build in the flexibility, you'll use it. Our (GE's) flexible machining center in Erie (Transportation Systems Business Operations) was originally designed to make six different (diesel electric locomotive) motor frames. Already, less than two years later, we've expanded it to handle 10 different motor frames."

In the Comptroller General's report to Congress in 1975, concerning the state of productivity in the United States compared to other industrialized nations, two salient points were revealed

- Of all time consumed in producing a part, only 5 percent is spent on the machine itself
- Of all time consumed on a machine tool, only 1½ percent is utilized in actual chip making

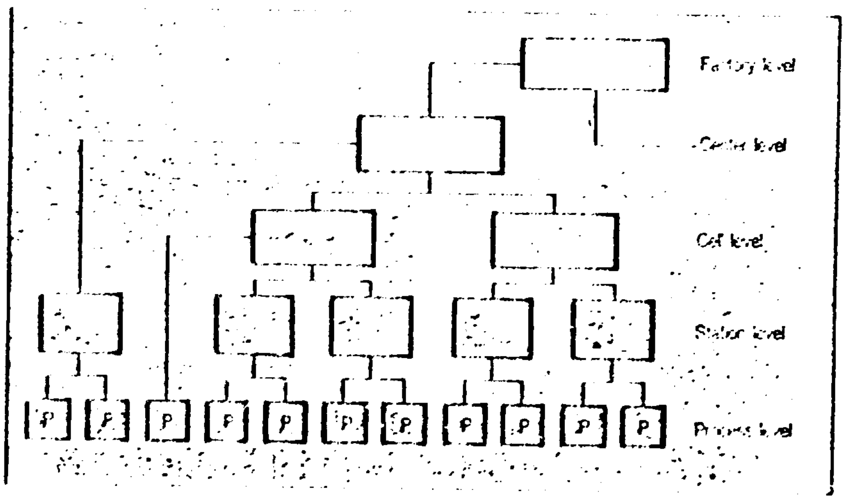
This means that 95 percent of all time consumed in making a part is expended in the handling of materials, recordkeeping, and similar activities. It is in these remaining areas that robotic work cells can significantly reduce manufacturing costs.

Thus we have three of the keys to profitability using robotic work cells

- Don't isolate the work cells from the rest of the plant
- Design the product to be made efficiently with automation
- Design your work cell as much as possible for product flexibility.

Why work cells in the first place?

Presently, machine tools are grouped together in the traditional department manner — with sawing machines in one area, milling machines, drill presses, lathes, grinders, etc all concentrated in their specific, separate locations. Distances between the various machines are expansive, requiring a great deal of movement of parts for each op-



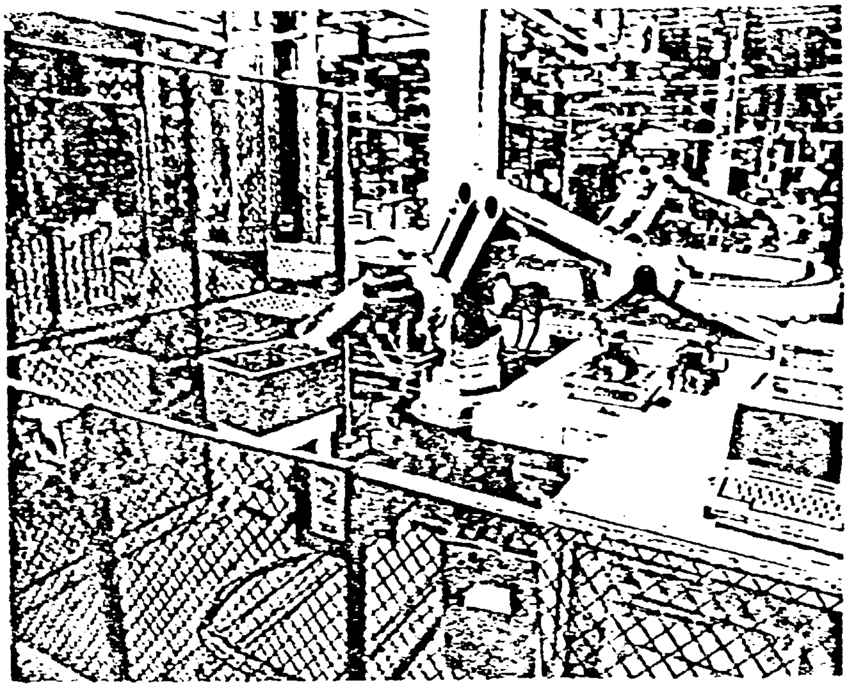
The U.S.A.F.'s ICAM project developed this factory automation "pyramidal" hierarchy. All communications are strictly vertical in nature. No same levels can communicate directly (horizontally) with each other [illegible] must be [illegible] for the transfer of the parts between machine tools, thereby generating a substantial amount of in-process inventory.

By proper classification of parts to be manufactured, those parts requiring similar machining operations can be grouped together for production on virtually the same machine tools. Hence, grouping the machine tools into a configuration which allows a robot to move parts between machine tool "stations" will allow the robot's movements to be optimized with the various production rates of each station. Profitability increases through the elimination of all wasted time while minimizing the in-process inventory.

Ken Susnjara, president of Thermwood Corp. (Dale, IN), commented in his book *A Manager's Guide to Industrial Robots* (Corinthian Press, 1982, p. 143) about a study conducted by Herbert Simon, the Nobel Prize winning psychology professor from Carnegie-Mellon University, which disclosed this unsettling fact: "When confronted with the choice between two or more alternatives, the American business executive does not, as people have been led to believe, choose the alternative which is most profitable. Faced with incomplete information, the executive chooses the direction that is closest to a successful decision made in the past. The executive generally will forego profits or the promise of profits for the apparent security of knowing the outcome."

Susnjara continued, "Because of this type of thinking, the 1970s saw American business continue to apply labor to applications where it seemed to make a lot of sense, since labor was abundant, not all that high priced, and quite flexible and adaptable. With the growth in the gross national product throughout the '70s and the availability of labor to drive that growth, it is somewhat surprising that this country enjoyed any level of productivity growth at all."

Thus in the 1980s, we have to reverse this kind of thinking and begin to apply programs to reindustrialize the country, and the integration of the robotic work cell into the factory environment is just the beginning.



In Chrysler's Huntsville, AL electronics plant, GE robots are now used to assemble and test spark control engine computers for all of the automotive company's passenger cars, trucks and vans. Eighteen robots are used for loading and unloading components and the computerized vision systems with cameras are used to identify up to 200 different part numbers.

Mitosis not metastasis

Mitosis is the regular, planned growth of a cell as compared to metastasis, or the unnatural growth of a cell. And good, careful planning is essential to the long-term profitable productivity that results from the proper implementation of the robotic work cell. Without it, [illegible] work cells could grow throughout the plant in an unplanned fashion every bit as potentially devastating to profitability as cancer is to the human body.

According to *Industrial Robots, a Summary and Forecast* (2nd Ed., 1983, Tech Tran Corp., Naperville, IL, pp. 100-102), "This essential first step (planning) in the implementation process can have a major impact in determining the eventual success of a robot installation." While this seems obvious, the Tech Tran report goes on to say: "Most companies now using robots did not conduct a formal audit of their manufacturing operations to evaluate the feasibility of using robots or to identify likely applications. However, they did conduct cost studies to evaluate the economics of using robots rather than manual labor. In typical manufacturing operations, it makes sense to conduct *both* a cost study and an audit of manufacturing operations."

In general, the types of applications suitable for robots are those in which there have been safety problems in the past and those which do not require judgement by the robot. The more hazardous, repetitive, fatiguing, or mind-numbing the task, the more justifiable a robot. Look for those areas in your manufacturing cycle that can be characterized by high levels of QC rejections or high levels of employee absenteeism.

In his address, (referenced above,) GE's Jim Baker has pointed out, "We (GE) don't allow individual pieces of automation equipment to be considered in isolation from the rest of the process. Tactically, it may be impossible to justify the cost of a robot, but strategically it may make good economic sense. If, with this robot, you can increase the percentage of time the inventory is being worked on, then you have a tremendous potential to reduce your material and overhead costs."

CAD modeling saves profits

The manual layout of a robotic work cell can be a very tedious task. In most applications, the robot arm must reach several machining stations in an optimum fashion. It's not unusual for the designer to lay out the work cell several times to overcome problems of reach, approach vectors, and possible collision with surrounding plant equipment while striving for just the right combination of machine positions and arm movements. All of this wasted time costs money.

To assist the robotic cell designer, ROBOT-SIM, a general-purpose robot simulation software product, was introduced at the ROBOTS 8 show in Detroit by the Calma Co. (General Electric Co., Sunnyvale, CA). According to Calma's Charles T. Thompson, there are eight basic functions which a CAD system must perform to develop simulations that are useful in designing a profitable industrial robot work cell:

- Design or modify the robot and its work cell.

- [illegible]
- [illegible] the work points and verify the robot's ability to move along that path
- Check for collisions of the robot with its environment
- Analyze the time required to perform a complete motion cycle
- Provide detailed information on the robot's dynamic behavior
- Flag any robot singularity condition
- Provide complete engineering documentation for the work cell design and for the simulated program

While the use of CAD systems has increased the efficiency of mechanical design by allowing multiple viewing angles and easy editing of drawings, nonetheless, there is still plenty of missing information. This lack of information prompted Bradley S. Thomas (General Electric Co., Robotics and Vision Systems Dept., Orlando, FL) to author "Graphic 3-D Simulation of Robotic Workcells," in which he describes a technique developed to enhance the use of a CAD system in the design of a robotic workcell.

According to Thomas, some of the missing information deals with the kinematic and dynamic considerations. The solution he offers is to create animated 3-D graphic displays which enable the robot cell designer to thoroughly test the newly created work cell before any hardware is assembled—sometimes even before any quotations are requested.

While the kinematic phase of the study can accurately place the arm along the "ideal" path, you still don't know when and how the arm and its load arrived. To truly optimize the robotic work cell, a dynamic simulation is also needed. The dynamic model of the workcell includes such information as: link masses and inertias, actuator speed, torque and inertia, and gripper and workpiece masses and inertias.

The combined kinematic and dynamic simulations provide answers such as exactly when the task point is reached and how much overshoot error is caused by the deceleration curve. The arm loading can be analyzed for special over-payload applications. Through the use of these tools, the robotic cell designer can optimize material throughput long before any capital equipment is ordered or installed.

Orchestration from cacophony

Different machine tools, robots, and transfer line components made by different manufacturers at different times do not *have* to speak the same language. In fact, they seldom do. To this Tower of Babel must come order, discipline and harmony if all [illegible] work cells to function at all, let alone profitably. One of the major problems facing the robotic cell implementor is how to get the various machines' controllers to talk to each other, ref. 1. Does he use the robot's control system to unify the various components, or does he use an external programmable controller or maybe even a host computer?

Through the efforts of the ICAM program (above), a factory control hierarchy terminology has been developed and is being adopted by aerospace and defense suppliers. At the bottom is the process level. The one or more processes are controlled by work station level systems. One or more work stations are controlled by cell level systems. One or more cell level systems report to center level systems. Finally, above one or more center level systems is found the factory level system. Similar hierarchical (pyramidical architectures) have been developed and espoused by GM (MAP—CE, July '84, pp. 73-75), Allen-Bradley (Vista 2000—CE, Apr. '84, p. 157), Honeywell (TDC3000—CE, July '84, pp. 76-78), and others. It should be noted that the ICAM model was created as a conceptual tool to assist the control engineer to implement automation of his factory, and real world applications may not always break conveniently into exactly the five levels described.

Adoption of any one of the above hierarchical structures should simplify the communications-compatibility efforts substantially, refs. 2 & 3. A major difference between the ICAM hierarchical format and the others cited is that under ICAM no controller ever *directly* communicates sideways to another controller on a common level.

Sideways communications on a common level add another dimension to the complexity of interconnecting the various islands of automation; the controller at each level must be able to communicate with the one below it, above it, and on either side of it. However, there is a tradeoff. Sideways communications speed up system response by minimizing how much information has to go up and eventually back down between levels.

Cell controller interfaces

The cell controller is the conduit of all instructions to and from the work stations (the various machine tools, transfer line components, and robots that make up the particular cell in question). Since the intelligence and capabilities of these various work stations varies from control files to high-level commands, the cell controller must also back up critical data structures [illegible] at the work stations and [illegible] data structures [illegible] work stations should lose them due to malfunctions.

The cell controller is also the interface between adjacent cells and the factory control hierarchical infrastructure. It provides the factory level systems with data such as the current capacity of the cell, maintenance requirements, quality results, and other information, as needed. All of these data have a direct impact on how the factory automation system functions. Without these data, the factory systems could not optimize the material throughput and provide the management information system with the necessary update reports.

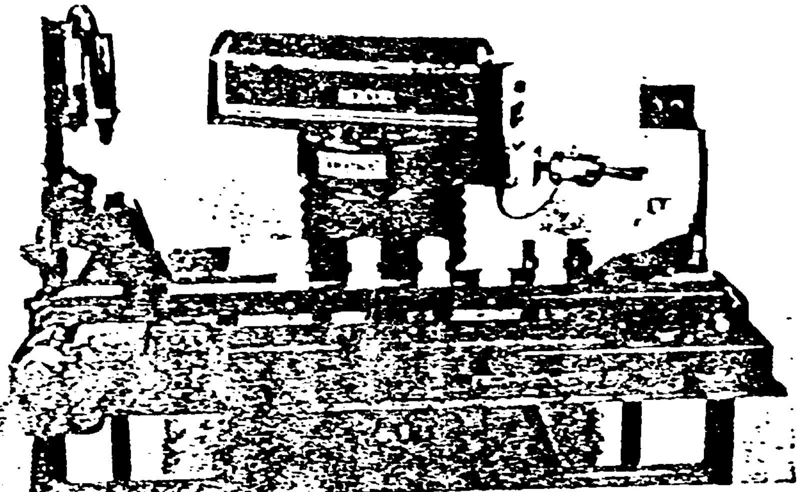
In addition to its communications tasks, there are at least seven internal services also performed by a robotic work cell controller:

- Controlling the loading of the cell
- Controlling the job's actual processing
- Controlling the job's movement through the cell.
- Managing processing resources within the cell
- Exception handling and diagnostics
- System monitoring
- Accumulation of historical performance data

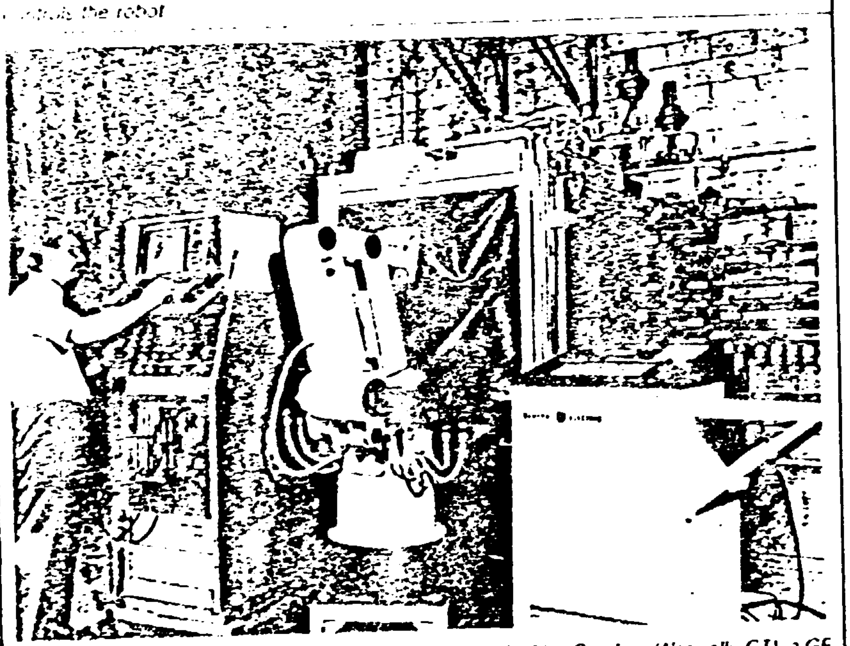
Printing press manufacturing cell

At the Graphics Systems Div. plant of Rockwell International, (Reading, PA), a GCA Corp. (Bedford, MA) Cirncell cell controller and Cirnnet factory local area network are being employed to provide supervisory level control in a cell that machines parts for several different models of commercial printing presses. The cell consists of three machine tools, a GCA overhead gantry robot, a GCA Cirnroc robot controller, an inspection machine, and a vision system. The Cirnnet enables the Cirncell cell controller to exchange data with all machine controllers and devices within the cell.

The machine tools and other non-GCA equipment are connected to Cirnnet via GCA's Network Interface Units (NIU). The GCA NIU is a microprocessor-based computer capable of talking directly to another NIU over the Cirnnet. Every NIU is equipped with firmware which accepts the language of the machine tool, controller, or whatever is connected to it. The NIU presently supports almost 100 protocols including those used by Allen Bradley, Cincinnati Milacron, and General Electric CNC controllers and programmable controllers. For upward compatibility, the NIU can presently interface with IBM, DEC, and Honeywell computers.



This workcell example from Amatrol (Jeffersonville, IN) has feeders for two parts: a cylindrical cason and a cap. The robot acquires the cason and places it in the clamp station in the center. It then gets a cap and places it on the cason. There's a precision fit between the cap and cason. The next step is for the robot to get an automatic screwdriver. It feeds a screw and screws the two parts together. The robot then takes the completed assembly to an inspection station. If the assembly holds tolerance, the robot palletizes the part. The entire robotic workcell is controlled through the discrete I/O ports resident in the same computer that controls the robot.



In this robotic work cell example supplied by Spadone Machine Co., Inc. (Norwalk, CT), a GE P50 robot is incorporated with Spadone's Vaqua liquid abrasive finishing system. Using this system, it's possible to deburr one part while the next coming down the line may only require a slight cleaning. The system controller instructs the robot how to process the parts.

Clean rooms need cells, too

People are *dirty!* In the semiconductor industry, the elimination of the filth accompanying people is essential to maintaining ultraclean environments. Automating these facilities while minimizing the number of people having access to them is a recurring theme in the semiconductor manufacturing industry.

Intelledex, Inc. (Corvallis, OR) has teamed up with Fluorocarbon to create a fully automatic, computer-controlled semiconductor wet processing system for use in Class 10 clean room environments. Designed to handle six in. wafers, each of the systems includes an Intelledex robot moving on floor-supported tracks (varying in length from 12 to 20 ft). In addition to its material handling tasks, the Intelledex robot is used to operate Fluorocarbon's Megasonic line of ultrasonic cleaning systems and Superclean [illegible] series of rinsers and dryers.

The robots will have sufficient intelligence to perform many different and complex tasks as well as to monitor variables such as fluid levels and acid temperatures. They will make decisions about skipping tanks, timing the movement of cassettes from tank to tank, and will select the proper recipe (processing specification) for a given product lot.

Electronic cam follower coordinates robotic cell activities

Using cams and cam followers is one way used to communicate necessary motion information to a mechanism. In the simplest case, a cam is usually a plate or cylinder which has a specifically shaped edge or groove cut in its surface. The cam follower rides on the edge or in the groove. The motions imparted on the cam follower by the changes in the cam's profile instruct the mechanism what to do and when to do it. In this physically dedicated system, if any change is needed, it's necessary to readjust the cam, rework the cam, or to provide a new one.

The dual axis automated cam follower, otherwise known as a programmable electronic cam, developed by Unico, Inc. (Franksville, WI), provides the robot workcell designer with a programmable electronic alternative to cross shafts, gearing, cam boxes, and other mechanical devices which have been used in the past to coordinate motions between several axes. Due to the increasing need to implement as much flexibility within the robot work cell as practical, eliminating dedicated parts that have to be adjusted or machined with electronically programmable alternatives eliminates the need to adjust, cut new, or alter existing cams whenever the product changes. Hence, the associated mechanism installation, maintenance, and reinstallation costs are eliminated, and setup time is reduced. Slaving several programmable electronic cam systems to a common master eliminates many additional mechanisms. □

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SECOND GENERATION ROBOTICS

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University of Hull,
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England.

1. Introduction

During the early years of their existence, Industrial Robots represented a solution in search of a problem. At the first International Symposium on Industrial Robots held in Chicago in 1970 (ref. 1) the delegates were treated to a brief catalogue of robot applications in industries which were invariably hot, smelly and involved jobs requiring a great deal of muscle power. This was the era when the industrial robot was a mere curiosity and its existence was known only to a relatively few informed industrialists. It was the combination of the industrial robot with the problem of spot welding automobile bodies which allowed the versatility of the industrial robot to be properly exploited. This single application transformed the industrial robot scene overnight which resulted in an escalation of the number of robots employed in industry coupled with a literal coverage in the media which in turn stimulated interest to extend the application of industrial robots to other industrial tasks.

Despite the increasing use of robots in industries having a hostile environment - for example dyecasting and forging - the greater success in application has hitherto been in areas where precise contact with the work place has not been an essential ingredient of the application (ref. 2). In addition to spot welding which falls into this category, paint spraying has been a popular and successful application and considerable success in recent years has been established with seam welding. While the industrial robot was originally conceived with a point-to-point mode of operation, it has been the continuous path mode of operation which has dominated most industrial robot applications. The situation existing now is that robots have become a natural and essential feature for the establishment of a manufacturing process particularly if this is being assembled on a green-field factory site. No longer do potential users need to wait for some adventurous industrialist to experiment with applications for the first time; most of this has been done and applications in the non-sensory handling and processing areas are well catalogued. Further, developments in robot structures and mechanisms now give the user a superb range of devices/products from which to choose as any visit to an exhibition of robots will demonstrate.

2. Where is 'generation 2' ?

From the very beginning of industrial robot technology, the prospect of intelligent control coupled to environmental sensors has been 'just around the corner'. That 'corner' is now over ten years old and still no really satisfactory realisation of the 'second generation' has been forthcoming. The impressive and promising demonstrations of 'artificial intelligence' at the First International Symposium (ref. 1) gave way to more relevant realisations of sensory interaction during the 1970's and a few commercial vision systems are now available (refs. 3, 4, 5). These however, represent the product of research of about a decade ago and demand a high contrast image for reliable operation.

Cost too plays its part as a deterrent in the sluggish approach of the 'second generation'. We see again the natural reluctance of industrial users not wishing to be first in the field. Acknowledging that substantial developments might exist behind the 'closed doors' of industrial confidentiality, only a few brave experiments towards the 'second generation' have appeared in the technical press. Incentive plays its part in the use of sensory control for certain applications and the microelectronic industry has provided a need for such radical thinking. Examples of this work have been published for some time (ref. 6, 7). The need for vision in this industry is associated with the high degree of visual feedback required during the act of device fabrication and assembly and the substantial geometric content of integrated circuit pellets has encouraged the application of machine vision to the problem of automatic alignment and wire bonding. The important aspect of this application which has demonstrated reliable operation must be the relative ease of control of the workplace and the illumination of the assembly area.

Can this success in the use of sensory control be regarded as a realisation of the 'generation 2' robot? Some would argue that it does but most would not accept the specialist mechanised handling as representative of versatile 'programmable automation'. Published attempts of sensory control of robots for shop-floor application are difficult to find. Single experimental applications of both visual and tactile feedback have been implemented although we have an example in the United Kingdom of a company marketing as a standard feature a vision controller for paint spraying (ref. 8) which is supported by several years of operating experience.

The application areas for the first generation robots are rarely associated with automated assembly excepting the applications of non-programmable placement devices (or robots). The breakthrough required to extend the application of programmable robots into automated assembly which will open the door to flexible manufacturing systems can only be realised with sensory control to support the assembly process. Despite recent developments in robot architecture (ref. 9), no programmable robot offers the kind of positioning precision to permit reliable assembly to take place without innovations of sensory control of the simplicity of the 'remote centre compliance' (ref. 10). Automated programmable assembly coupled with sensory interactive handling represents the goal which best defines 'generation 2' robotics. The manufacturing areas which involve small to medium sized batches dominate in the industrial scene and those are the areas which are starved of automated solutions. To achieve success in this sector, a great deal of work is still required before the flexibility offered by highly expensive 'generation 2' devices can be justified.

3. Vision research

It is perhaps vision more than the senses of touch and hearing which has attracted the greatest research effort. However, robot vision is frequently confused with vision applied to automated inspection and even the artificial intelligence aspects of scene analysis. If an uniformed comparison is made between the technology of picture processing and the requirements of robot vision it is not possible to reconcile the apparent divide which exists between the two.

The essential requirements for success in robot vision might be summarised as follows:

- low cost
- reliable operation
- fundamental simplicity
- fast image processing
- ease of scene illumination

These requirements are often diametrically opposed to the results of research effort published by research organisations. The processing of grey-scale images at high resolution often provides impressive results but inevitably this is achieved at the expense of processor architecture and processing time. Dedicated image processing systems (ref. 11) will attack the problem of processing speed in a most impressive way but there is often a desire on the part of many researchers to identify an area of technological challenge in image processing to satisfy their own research motivation rather than attempt a simplification of the imaging problems.

Probably the single aspect which causes difficulty but often overlooked is the control of illumination of the work area. This problem has been attacked by some researchers using 'planes of light' (ref. 12, 13) which might be regarded as a primitive application of structured lighting i.e. super-imposing on the work area a geometric pattern of light which is distorted by the work pieces. The success of this approach is manifested in the simplicity of binary image processing and a reduction in the magnitude of visual data to be analysed (ref. 14). Developments of early demonstrations of robot vision using back lighting of the work area have reached a stage of restricted industrial application (ref. 15). However, a feature of sensory techniques which have industrial potential, is that they are often application specific and cannot be applied generally.

The experiments linking image processing of televised images with robot applications (for example ref. 16). are in their infancy at present; the cost is high and the reliability of image processing is unlikely to be satisfactory for some time to come.

4. Image resolution

Sensing for robot applications is not dependent on a relentless pursuit for devices with higher and higher resolution. The fundamental consideration must be in the selection of *optimum* resolution for the task to be executed. There is a tendency to assume that the higher the resolution then the greater is the application range for the system. At this point in our evolution, we are not exploiting the 'state of the art' as much as we should. Considerable success has been achieved using a resolution as low as 50 x 50 (ref. 6). With serial processing architectures, this resolution will generate quite sufficient grey-scale data to test the ingenuity of image processing algorithms! Should processing time approach about 0.5 seconds, this will be noticeable in a robot associated with handling. However, for welding applications, the image processing time must be even faster.

High resolution systems are required in applications involving automated inspection and picture data retrieval where speed is sometimes not such an important criterion. This must not be confused with the needs of sensory robot systems.

5. The sensor crisis

Perhaps the key issue in the production of the sensory robot is the availability of suitable sensors. The following represents a summary of sensing requirements for robot applications:

- presence
- range
- single axis measurement (or displacement)
- 2-dimensional location/position
- 3-dimensional location/position
- thermal
- force

for which the following sensing devices or methods are available.

Vision

- Photo-detector
- Linear array
- Area array
- TV camera
- Laser (triangulation)
- Laser (time of flight)
- Optical fibre

Acoustic

- Ultrasonic detectors/emitters
- Ultrasonic arrays
- Microphones (voice control)

Tactile

- Probe
- Strain gauge
- Piezoelectric
- Carbon materials
- Discrete arrays
- Integrated arrays

Other

- Infra red
- Radar
- Magnetic proximity
- Ionising radiation

The only satisfactory location for sensors is on the robot manipulator itself at or near the end effector (ref. 14, 17). Locating an image sensor above the work area of a robot suffers from the disadvantage that the robot manipulator will obscure its own work area and the metric displacement of the end effector from its destination must be measured in an absolute rather than a relative way. Siting the sensor on the end effector allows relative measurements to be taken reducing considerably the need for calibration of mechanical position and the need for imaging linearity. Sensory feedback in this situation can be reduced to the simplicity of range finding in some applications.

What is missing from the sensor market are devices specifically tailored to be integrated close to the gripper jaws. The promise of solid-state arrays for this particular application has not materialised which is primarily due to the commercial incentives associated with the television industry. It might be accurate to predict that over the next decade imaging devices manufactured primarily for the television market will be both small and cheap enough to be useful in robot applications. However, at present, area array cameras are extremely expensive and, while smaller than most thermionic tube cameras, are far too large to be installed in the region of a gripper. Most of the early prototype arrays of modest resolution have been abandoned.

It is not an exaggeration to suggest that no imaging sensors exist which are ideally suited for robot applications. The use of dynamic RAM devices for image purposes (ref. 17) has proved to be a minor breakthrough and gives an indication of the rugged approach which is needed to achieve success. Some researchers have attacked the problem of size reduction by using coherent fibre optic to retrieve an image from the gripper area (ref. 16) which imposes a cost penalty on the total system. This approach can, however, exploit a fundamental property of optical fibre in that a bundle of coherent fibres can be sub-divided to allow a single high-resolution imaging device to be used to retrieve and combine a number of lower resolution images from various parts of the work area including the gripper - with each subdivided bundle associated with its own optical arrangements (refs. 18, 19).

Linear arrays have been used in situations involving parts moving on a conveyor in such a way that mechanical motion is used to generate one axis of a 2-dimensional image (refs. 12, 18). There is no reason why the same technique should not be associated with a robot manipulated by using the motion of the end effector to generate a 2-dimensional image. Also implied here is the possibility of using circular scanning of the work area or even taking a stationary image from a linear array.

Tactile sensing is required in situations involving placement. Both active and passive compliant sensors (ref. 20, 10) have not only been successfully demonstrated but have experienced a period of development and application in the field. The situation surrounding tactile array sensors is quite different. Because the tactile arrays are essentially discrete in design, they are inevitably clumsy and are associated with very low resolution. Interesting experiments have been reported (ref. 21, 22, 23, 24) and an exciting development for a VLSI tactile sensor is to be published (ref. 25).

Experiments with range sensing have been liberally researched and some success has been achieved with acoustic sensors and optical sensors (including lasers). The whisker probe (ref. 24) can now be replaced by a laser alternative with obvious advantages. Laser range finding is well developed but under-used in robot applications although the use of laser probes sited on the end effector of an industrial robot makes a natural automated dimensional inspection system.

It is clear from this brief catalogue of sensing methods that a great deal of chaos surrounds the sensor world. What we must work towards is some element of modularity in sensor design to allow for the optimum sensing method to be incorporated into a given application. No single sensor can provide the solution to all problems and bigger does not always mean better. However, the recent exciting developments in 'smart sensors' which incorporate primitive image processing (front-end processing) will be most welcome. A comprehensive survey and assessment of robotic sensors has been published by Nitzan (ref. 26).

6. Languages and Software

The involvement of the stored-program computer in the present generation of robots does no more than to provide an alternative to a hard-wired controller excepting that the computer provides an integrated memory facility to retain individual 'programs'.

Software and languages became a reality for most users with the introduction of VAL (ref. 27) which incorporates the capability to interpolate linear motion between two points and provides for co-ordinate transformation of axes. Further, VAL allows for transformation between vision and machine co-ordinates (ref. 28). Machine training or learning using VAL can be achieved 'off-line' rather than the 'teach by showing' which is the method used by the majority of present generation robots.

Work is now under way on languages for assembly (ref. 29, 30) which will give to the sensory robot system autonomy of action within the requirements of the assembly task. Further, a common assembly language will permit the same instructions to be repeated on different robot hardware in the same way that computer programs written in a common language can be executed on different machines. The lesson to be learned here is that we must discipline ourselves to a common assembly language before a proliferation of languages creates a situation disorder. It is still early days to consider an assembly task being executed by an 'off line' assembly language as part of a CAD/CAM operation. One of the stepping stones required in this revolutionary process is the establishment of some 'bench marks' to compare and test the relative merits of assembly languages.

7. Concluding remarks

The ingredients which comprise the second generation robot are:

- mechanisms with speed and precision
- cheap and reliable sensors
- elegant and rugged software

In all of these areas there exists a significant deficiency of development and perhaps a need for an innovative breakthrough. We have seen previously the shortfall in sensor requirements and the need for good supporting software has only been admitted in recent times. With the exception of mechanisms specifically designed for dedicated tasks, no existing robot device alone can really provide the precision necessary for assembly operations. A promising way to proceed is to use a programmable high speed manipulator for coarse positioning, coupled with a 'floating' table which incorporates features for fine positioning (ref. 31).

When it is remembered that *research* demonstrations of 'generation 2' robots have been available over the past decade (ref. 32,33,34,35,36,37) it is salutory to recognise that predictions for the future made over this period have not been realised. A survey of the current situation in robot vision has been published recently (ref. 38). It would be a brave person who now predicted where and when the 'generation 2' robot would take its place in industry. With the wisdom of hindsight we know that there is still a vast amount of research and development required coupled with an industrial need for a 'generation 2' robot. Perhaps this need will first appear in the textile, pottery or confectionery industries (ref. 39) to provide the 'shot in the arm' for 'generation 2' just as spot welding did for 'generation 1' a decade ago.

Over the past two years, the United Kingdom has introduced government funding to aid and support industrial applications as well as providing a co-ordination programme of research and development in the universities. Surveys of industrial requirements and research partnerships in the U.K. have recently been published (ref. 40, 41).

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III.REFERENCE LITERATURE

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IV. MANUFACTURERS AND RESEARCH INSTITUTES

Each of the following lists must be incomplete. Worldwide there are a lot of manufacturers as well as research and development institutions dealing with industrial robots. Therefore only some of them may be included

List of robot manufacturers

The following list contains selected manufacturers of industrial robots worldwide.

AABO ANDERSEN APS
Hejrevaenget 7, Thuro
DK 75 Svenborg
Danmark

AEG-TELEFUNKEN
Industrie-Anlagen, A41 U17
Lyoner Straße 56
D-6000 Frankfurt/Main 71

AJAX MACHINE TOOL CO.LTD.
347/855 Ringwood Road
Bournemouth BH11 8NE
England

AMERICAN ROBOT CO.
354 Hockstown Road
Clinton, PA 15026
USA

ASEA ELECTRONICS DIVISION
S-72183 Vaesteras
Sweden

ATLAS COPCO TOOLS AB

Sickla Allee 5
S-10460 Stockholm
Sweden

AUTOMATIX
1000 Technology Drive
Billerica, MA 01821
USA

BENDIX
21238 Bridge Street
Southfield, MI 48037
USA

BOSCH INDUSTRIEAUSRUSTUNG
Postfach 300220
Kruppstr. 1
D-7000 Stuttgart 30

CINCINNATI
215 S.West Street
Lebanon, OH 45209
USA

CLOOS SCHWEISSTECHNIK GMBH
Postfach 121
D-6342 Haiger
F.R.G.

COMAU S.P.A.
Via Rivalta 30
I-10095 Grugliasco (Torino)
Italy

DAINICHIKIKO CO, LTD.
Kusai Cho
Nakokoma-Gum Yamanachi

Japan 400-04

DEA S.P.A.
Corso Torino 70
I-10024 Moncalieri Torino
Italy

DEVILBISS
300 Philips Ave.
Toledo, OH 43612
USA

FANUC
5-1 Ashigaoka 3-Chome
J- Tokyo 191
Japan

GEBR. FELSS GMBH
Stein 2
D-7535 Königsbach
F.R.G.

GENERAL ELECTRIC CO.
P.O.Box 17500
Orlando, FL 32860-7500
USA

FIBRO GMBH WERK II
Postfach 1120
D-6954 Hassmersheim
F.R.G.

FUJI ELECTRIC CO.LTD.
Shin-Yurakucho Bldg.
12-1, Yura Kucho 1-chome
Chiyoda-Ku, Tokyo 100
Japan

GRACO Robotics Inc.
12898 Westmore Av.
Livonia, Michigan 48150
USA

HALL AUTOMATION LTD.
Boughton Road
Rugby, Warwicks., CV21 1UB
England

HIRATA
5-4 Myotaiji-Machi
Kumamotu 860
Japan

HITACHI LTD.
Nihon Bldg. 2-6-2 Ohtemachi
Chiyoda-Ku, Tokyo
Japan

IBM ADVANCED MANUFACTURING
Boca Raton
Florida
USA

IGM GMBH
Straße 2A, Halle M8
A-2351 Wr.Neudorf
Austria

INTELLEDEX INC.
33840 Eastgate Circle
Corvalls, Oregon 97 333
USA

INTERNATIONAL ROBOMATION/INTELLIGENCE

2281 Las Palmas Drive
Carlsbad, California 92008
USA

KAWASAKI HEAVY IND.LTD.
4-1, Hamamatsu-cho
Minato-Ku, Tokyo
Japan

KUKA (IWKA KELLER & KNAPPICH)
Postfach 43 13 49
Blücherstr. 144
D-8900 Augsburg 43

LAMBERTON ROBOTICS
26 Gartherrie Road
Strathclyde ML52 DL
Scotland

MANTEC
Gründlacherstr.248
D-8540 Fürth
F.R.G.

MATSUSHITA LTD.
3-2, Minami semba
Minami-Ku, Osaka 542
Japan

MICROBO
Avenue Beauregard 3
CH-2035 Corcelles
Switzerland

MICROBOT INC.
453-H Ravendale Dr.
Calieornia 94043

USA

MITSUBISHI LTD.
1-1 Daikou-Cho
Higashi-Ku, Nagoya City
Japan

NACHI FUJIKOSHI CO.
3-5 Shiba Hamamatu-Cho
J- Tokyo
Japan

NAKANIPPON ELECTRONICS CO.,LTD
4330 gamacho Kita-Ku
Nagoya 462
Japan

OLIVETTI
Via Torino 608
I-10090 S.Bernardo D'Ivrea
Italy

PENDAR ROBOTICS
EBBW Vale
Gwent NP3 5SD
England

PRAB INC.
6007 Sprinkle Road
Kalamazoo, MI 49003
USA

REIHS GMBH & CO
Postfach 1160
Im Weiding 1-4
D-8753 Obernburg
F.R.G.

RENAULT
Centre Parly 2, P.B.70
78150 Le Chesnay
France

SIMMERING-GRAZ-PAUKER AG
Mariahilferstr. 32
A-1071 Wien
Austria

SIEMENS AG
Postfach 120
Wernerwerkdamm 17-20
D-1000 Berlin 13

TOSHIBA, EVERSHED ROBOTICS LTD.
Bridge Road, Chertsey
Surrey KT 16 BLJ
England

TRALLFA NILS UNDERHAUG A/S
Postfach 113
N-4341 Bryne
Norway

UNIMATION INC.
Shelter Rock Lane
USA-Danbury, Conn.06810
USA

VOEST-ALPINE AG
Postfach 2
A-4010 Linz
Austria

VOLKSWAGENWERK AG

Postfach
Industrieverkauf VD-3
D-3180 Wolfsburg

WESTINGHOUSE ELECTRIC CO.
400 Media
Pittsburg, PA 15205
USA

YASKAWA ELECTRIC MFG.CO.LTD.
Ohtemachi, Chioda-Ku
J- Tokyo
Japan

ZAHNRADFABRIK FRIEDRICHSHAFEN AG.
Postfach 2520
Löwentaler Straße 100
D-7990 Friedrichshafen 1

Research Institutions and Universities

In the following some Research Institutions and University Institutes dealing with robotics and related fields are collected.

AUSTRIA

ARGE "Industrieroboter und Handhabungsgeräte"
c/o Inst.für Mechanik, 309
Techn.Universität Wien
Karlsplatz 13, A-1040 Wien
Austria

Inst.für Fertigungstechnik, 311
Techn.Universität Wien
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