ROBOTICS
IN
PRACTICE

Management and applications of industrial robots

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Robotics in Practice

Management and applications of industrial robots

Joseph F. Engelberger

With a Foreword by Isaac Asimov

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Foreword

THE REAL THING

by Isaac Asimov

Back in 1939, when I was still a teenager, I began to write (and publish) a series of stories about robots which, for the first time in science fiction, were pictured as having been deliberately engineered to do their job safely. They were not intended to be creaky Gothic menaces, nor outlets for mawkish sentiment. They were simply well-designed machines.

Beginning in 1942, I crystallized this notion in what I called 'The Three Laws of Robotics' and, in 1950, nine of my robot stories were collected into a book, *I, Robot*.

I did not at that time seriously believe that I would live to see robots in action and robotics becoming a booming industry. . . . Yet here we are, better yet, I am alive to see it.

But then, why shouldn't they be with us? Robots fulfil an important role in industry. They do simple and repetitive jobs more steadily, more reliably, and more uncomplainingly than a human being could – or should.

Does a robot displace a human being? Certainly, but he does so at a job that, simply because a robot *can* do it, is beneath the dignity of a human being; a job that is no more than mindless drudgery. Better and more human jobs can be found for human beings – and should.

Of course, the robots that now exist and that are described in fascinating detail in this book that you are holding, are not yet as complex, versatile and intelligent as the imaginary robots of *I, Robot,* but give the engineers time!

There will be steady advances in robotics, and, as in my teenage imagination, robots will shoulder more and more of the drudgery of the world's work, so that human beings can have more and more time to take care of its creative and joyous aspects.

Author's preface

When Pygmalion fell in love with his beautiful creation Galatea, Venus compassionately breathed life into the marble statue and Pygmalion was blessed with an exquisite robot wife. One may presume that after the honeymoon, he put her to work. That is what this book is about, putting robots to work.

Others have and will continue to write about robot design. It is a volatile field that draws upon many technical disciplines for ever greater sophistication. To date, robots have largely been insensate, but roboticists are striving to correct this deficiency. When robots do boast of sight and touch, the list of applications (Part II), will merit a large supplement; but, meanwhile, there is much good work for senseless robots to do. The process of selecting suitable jobs and then optimizing the work place for successful economic employment of robots has been evolving since the first Unimate robot was installed to tend a die casting machine in 1961.

This author has been privy to the bulk of the successful robot installations (and to the dismal failures as well), inasmuch as Unimation Inc., with over 3000 Unimates in the field, has been the dominant manufacturer. Moreover, in application areas where Unimation Inc. experience is limited (i.e., spray painting), other robot manufacturers have been generous with application data.

Some debts should be acknowledged before attempting an exhaustive discourse on the business of putting robots to work. First of all, there was Isaac Asimov who conveniently began his prolific writing career at a tender age with robotics as a theme (thus coining the name of the science and catching the fancy of this 1940's Columbia University physics major). Then, one George C. Devol propitiously turned up at a cocktail party in 1956 with a tall tale of a patent application labeled *Programmed Article Transfer.* It was issued in 1961 as U.S. Patent 2,988,237, and good friend George went on to amass numerous other patents in robotics to the ultimate benefit of Unimation Inc.

Innovations don't happen without financial support. An imaginative entrepreneur, Norman I. Schafler, founder and still chief executive at Condec Corporation, dug down first and he was later joined by Champ Carry, then Chairman of Pullman Incorporated.

After the first industrial robot installation of 1961, there was a lot of 'hanging-in-there' to do. Not only were there remaining technical problems, but there were some formidable institutional barriers. To many manufacturing executives robotics remained science fiction fantasy. Unimation Inc. did not show a profit until 1975.

In the 60's, there were some tentative and, for the most part, abortive attempts at developing competitive robots, but none blossomed to help carry the early institutional load. Yet robotics was an idea whose time had come. By the early 1970's, the artificial intelligence community swung some of academe's attention to robotics. That interest earned support from various national governments (and today this is mounting). The Japanese jumped in with great enthusiasm; and the Japan Industrial Robot Association (JIRA) was started in 1971. Kawasaki Heavy Industries had taken a license from Unimation Inc. well before, in 1968.

In 1973, Warnecke and Schrafft of Stuttgart University wrote their book, *Industrie Roboter,* in which they uncritically catalogued every robot developed that they could unearth. They listed 71 firms as being developers of robots. By 1978, there had been some 200 efforts, most of which were abandoned. Survivors who may be taken seriously are listed in the Appendix. Only those who are in production and who back up their product with complete customer service are included in the list.

The USA could not boast of enough committed manufacturers to form an association until 1975, when the Robot Institute of America was formed. By 1978, association membership comprised 10 robot manufacturers, three robot accessory manufacturers, 25 users and three research organizations. The British Robot Association (BRA), is even younger, getting started in 1977 with strong support from academia. Little robot manufacturing has as yet been started in the UK, but research interest is strong and BRA starts out with an avant garde coterie of users and would-be users. Robot organizations are springing up throughout Europe. One of the hottest technical conference topics is robotics. The International Symposium on Industrial Robots (ISIR), is an annual event, with its venue chosen from European countries, Japan and the USA.

As with any new field, development directions are legion. Some have sought to develop sophisticated computer-controlled machines, but many more have elected to make simpler devices, with mechanical stops and pegboard programming. Robots come in all shapes and sizes, some handling only a few grams while others can cope with as much as 1000 kg. Arm coordinates can be polar, cylindrical, cartesian or revolute. Muscle power is hydraulic, pneumatic or electric.

This book considers the place of robots in factories and it considers the types available and it makes much of economics being the driving influence. An attempt is also made to predict both technological direction and the sociological implications for the last two decades of this century.

There is no question but that robotics has become an international industry, complete with all the trappings of product choice, industry association, government encouragement, public interest, a research coterie and the promise of explosive growth. Such growth of the industrial robotics industry depends upon broad acceptance of this new technology by hard goods manufacturers, a notoriously sceptical and conservative clientele. It is hoped that this book will serve to allay ill-founded concern and to eliminate some of the pain that inevitably accompanies the adoption of unfamiliar concepts.

Joseph F. Engelberger
September 1980

PART 1
Fundamentals and management

Chapter 1

Robot use in manufacturing

Robots entered the English vocabulary with the translation of Karel Capek's play *R.U.R.* (Rossum's Universal Robots) in 1923. Capek was a Czech, and in his native language the word robot simply meant a worker. In the play, robots were the humanoid creations of Rossum and his son, constructed in the fond hope that they would perform obediently in the service of man. Now, thanks to Capek and a generation of science fiction writers, everyone knows what a robot is. The popular conception is a mechanical man, crammed full of near-miraculous components, and capable of clumsy imitations of human actions and speech. They are generally thought to combine superhuman strength with subhuman intelligence. Robots are often endowed with sinister intentions, so that the specter of a robot army marching against mankind has been a popular recurring theme in science fiction.

Fortunately, Isaac Asimov in the 1940's took it upon himself to envision robots in a happier light. Asimov's robots were benevolent. In a series of robotic stories that are both ingenious and delightful, Asimov postulated roboticists with the wisdom to design robots that contained inviolable control circuitry to insure their always 'keeping their place'. The Three Laws of Robotics remain worthy design standards:

1. A robot must not harm a human being, nor through inaction allow one to come to harm.
2. A robot must always obey human beings, unless that is in conflict with the first law.
3. A robot must protect itself from harm, unless that is in conflict with the first or second laws.

Capek gave us 'robot'. Asimov coined the name of the trade, 'robotics', and he provided all of us roboticists with an ethic.

Evolution of industrial robots

Although functioning, exact replicas of men remain technologically impossible. It is nevertheless attractive to imagine an industrial world where robots could perform all the menial, tedious, repetitive, dangerous and otherwise unpleasant jobs. Why not factories with robot labor forces? This dream becomes less far fetched as soon as we stop thinking of robots in purely anthropomorphic terms. Capek caused Rossum to say, 'A man is something that feels happy, plays the piano, likes going for a walk, and, in fact, wants to do a whole lot of things that are really unnecessary . . . But a working machine must not play the piano, must not feel happy, must not do a whole lot of other things. Everything that doesn't contribute directly to the progress of work should be eliminated.'

By considering what a man has to do at a typical machine station, it should be possible to devise a list of corresponding characteristics that a robot must possess if it is to replace him. And now a most important fact emerges. In order to increase the ratio of output to labor cost, most manufacturers have broken down their processes into small elements. Each operator has to learn only one sequence of operations, which he is then required to perform over and over again. The degree of skill is low, and there is little to learn. Thus the manufacturer is able to employ unskilled labor. And if the job has been simplified for the man, it has also been simplified for his possible robot successor – simplified, in fact, to the point where robots have become a present-day practicability.

Picture the typical unskilled or semi-skilled operative at his machine station. For the purposes of this discussion the type of machine or process hardly matters. It can be assumed that, in most cases, the operator's first job is to load the machine. Loading involves selecting the workpiece or raw materials, picking up, and placing the part or materials into the machine. Usually, it is necessary to ensure that the workpiece is correctly oriented, although there are exceptions such as objects which are spherical, or where powders or liquids are being loaded for processing. Next, a series of levers, handles, buttons or other controls have to be operated in a sequence that causes the machine to carry out its work. Then, the man unloads the machine by removing the workpiece and stacking it into a bin, or on to a shelf or conveyor. The man may be expected to perform a simple visual or mechanical check at the end of this cycle, in case the product is defective.

This simple production cycle must be repeated over and over again, to cease when the batch has been finished, the materials have run out, the machine breaks down or needs resetting, or the man goes home at the end of his shift, stops to eat, goes away for some other natural purpose, goes on strike, or simply feels tired. Sometimes, the man will continue to operate the process in spite of illness or fatigue, in which case there is a possibility of a stream of defective parts being produced before these are noticed by an independent inspector or quality controller. This situation contains the factors from which a theoretical robot specification can be compiled.

Consider, step by step, the narrative contained in the previous two paragraphs. By analyzing the human capabilities and failings involved, it should be possible to view each ingredient in robot terms and build up a list of attributes that no desirable robot should be without. This comparative exercise is best achieved by using a table, and this is shown at Figure 1.1. The left hand side of this table lists activities and other factors which are relevant to any operative working at a typical machine station. In the center column, each entry is a comment on the performance of a human operative. Possibilities for a robot substitute are given in the right hand column.

A specification for an industrial robot must obviously exclude any requirement that cannot be achieved in practice. Every feature specified must be within the scope of contemporary engineering knowledge and practice. The resulting robot must not be too big, too heavy or too expensive. It has to be reliable, and capable of doing its job for hour after hour without undue fuss. Thirty years ago these conditions could not have been met. In more recent times, the development of microelectronics, advances in computer technology, and the availability of reliable electromechanical and hydromechanical servo mechanisms have all contributed to the elevation of robots from fiction to fact.

The notes in the right hand column of Figure 1.1 provide the source material for a summary of the characteristics essential to any robot that is intended to replace a man or woman at a machine station. Here is that basic summary:

○ A hand which can grip or release the workpiece
○ An arm which can move the hand in three planes
○ A wrist for the arm, with three articulations
○ Sufficient limb power to lift and maneuver the workpiece
○ Manual controls with which a person can operate the limb
○ A memory, which can record manual operations
○ Automatic means for controlling the limb from the memory
○ Ability to function at a speed not less than that of a person
○ Reliability

Physical human properties that are not essential to production, or are impracticable to achieve at the current state of the art, are not included in the basic list. Thus, the industrial robot is not given legs, because it does not need to walk in order to operate a machine. Why provide two arms if the robot can manage with only one? And, because of current technological limitations, the robot is not expected to enjoy the human senses of taste, smell, hearing, touch or sight. The last two senses will be added, and soon at that. A senseless robot is a far cry from the robot of popular fiction, but it is the design concept on which several kinds of robots have been built and deployed profitably in the manufacturing industry.

It is a mistake to limit the robot specification to a contrivance that

FUNCTION	HUMAN OPERATIVE		ROBOT OPERATIVE	
Select workpiece	H1	Uses senses of sight and touch.	R1	Visual methods are prohibitively difficult at the present state of the art. The practicable methods are restricted to sensing physical contact, and by a pre-programmed command which directs the robot to the workpiece location.
Picking up	H2	Uses combination of arms, hands and body. May need mechanical assistance with heavy lifts.	R2	Strictly, the robot only needs one arm and a hand, although these must be jointed to allow the hand to move in three dimensions and to swivel. The use of hydraulic power can produce greater lifting capacity than a man's.
Placing	H3	Similar to H2, but uses his eyes to ensure that the workpiece is correctly orientated.	R3	Similar to R2, but without the sense of sight, orientation becomes difficult. A robot operator needs workpieces that are presented to it in some pre-defined and constant attitude.
Operate machine	H4	Uses any one or all of his five senses to follow the operation of the machine and activate the controls as necessary. Has a memory, with which he can learn the sequence and timing of operations.	R4	Because it is not able to see, hear, or otherwise witness the progress of the machine, a robot must be pre-programmed to carry out its operations according to a timed sequence. A man has to do the teaching, and the robot has to have an internal memory to store the information. Computer technology has made this possible.
Unload machine	H5	This is similar to H2.	R5	Similar to R2.
Stack the workpiece	H6	This is similar to H3.	R6	Similar to R3, but orientation is less of a problem, because the machine will usually be one which holds every workpiece in the same position and attitude.
Inspect the workpiece	H7	A man should be capable of inspecting, as required, using his senses of sight and touch, or by using gauges and other measuring equipment. He is able to speak, and to tell the foreman of any machine problem.	R7	A robot would be capable of inspection by automatic gauging, by probing, and by telemetry or dataloging. Although not able to speak, the robot could be designed to give an audible or other warning of any defect in the workpiece.
Machine breakdown	H8	Able to use any one of his senses to perceive possible trouble. For example, he could recognise the smell from a hot motor, and switch off the machine.	R8	A robot would be capable of detecting a machine breakdown only where this produce defects in the workpieces that the robot could detect, or where telemetry points were set up in the machine.
Machine setting	H9	This operative has been defined in the text of Chapter 1 as unskilled or semi-skilled. He must, therefore, expect to have to call for skilled assistance whenever the machine needs resetting or retooling.	R9	The robot could be programmed to stop after a period calculated to allow for tool wear. It is also practicable to command the robot to probe the workpiece and/or the machine for broken drills, taps, reamers and other tools. A skilled human operator is needed to carry out rectification and resetting.
Shift periods	H10	A man has to leave for home after a shift period of between eight and twelve hours. He has to be mobile – able to walk and run.	R10	There is no need for a robot to be self-mobile. It can be fixed to the floor, and commanded to work round the clock every day. Where three shifts are operated within 24 hours on one machine, a robot operative can take the place of three men – more men if the robot can be set up between two or more adjacent machines that it can operate in sequence.
Workbreaks	H11	A man has to take time off work for eating, and for other physical needs.	R11	Robots do not need time off for eating or for other natural functions. They will be subject to down time for maintenance and, however reliable the design, there will inevitably be occasional breakdowns.
Strikes, go-slows and overtime bans	H12	Collective disruptive action from the labor force is a problem that can hit any production plant.	R12	A robot will obey commands slavishly and there is no labor organization for robots.
Illness and fatigue	H13	Men get tired, sometimes feel below par, and they may be absent from the workplace when they fall sick. These conditions can be aggravated or caused by unpleasant working accommodation (heat, noise, toxic fumes, smells, cramped space, etc).	R13	Robots can be expected to break down very occasionally (see R11). But it is possible to design robots that can operate in extreme conditions which might damage a man's mental or physical health – such as noise, heat, vibration, noxious fumes, smells, cramped work space and even radioactivity.

Figure 1.1 *Comparison of human and robot characteristics*

A robot is not capable of performing all the tasks that its human counterpart can achieve. Conversely, robots are able to do some jobs better than men, especially where these demand repetitive work for long periods under arduous conditions.

can simply attempt to imitate its human prototype. We know that, within the limitations of current technology, any real life industrial robot is going to be a machine that lacks many human senses and sensibilities. As mere human imitators, therefore, robots are likely to be very inferior models. But robots can be conceived with other capabilities, which are not anthropomorphic, and which can compensate in many respects for their inability to see and feel.

Robots should be capable of outperforming men in hostile working environments, where noise, vibration, smells or danger act adversely on the physiological system. Robots do not have to stop for eating. They have no wives to go home to. They do not get tired, they can work right round the clock. Unlike men, robots are not going to be gregarious creations, and we should not expect to find them participating in drama groups, stamp collecting societies, sports clubs or the like.

The use of hydraulic or electric power gives a robot more potential muscle than a man or woman. The design specification should take all these factors into account, so that the resulting product is extended into a robot which exploits its mechanical advantages as fully as possible.

Robot controls became feasible through the advent of digital logic and miniaturized solid state electronics – the very same techniques used in computers and in numerically controlled (NC) machine tools. This common root means that communication links can be established between robots and computers, and between robots and NC machines. This opens up exciting future possibilities for operating robots directly from computers, or for synchronizing them with NC machines. Companies which use computers for design (CAD) might even be able to have their computer design the product and produce the robot control program, so that not only the human machine operator is replaced, but the draftsman as well. These prospects are discussed in later chapters, but they illustrate the need to compile a specification which, while avoiding unnecessary human attributes, contains all the advantages that robots can offer.

Such a specification can now be drawn up. By starting from human performance, by taking Capek's advice to strip away factors not essential to the progress of work, and then by adding facilities available from today's technology, we arrive at the extended specification shown in Figure 1.2.

Near relations of the robot

Even though everyone knows what a robot is, this presumptive knowledge is richly diverse. Therefore, a book devoted to the use of robots ought to attempt definition, and then put to bed related technologies that don't qualify and that therefore will not be considered herein.

1 A hand, capable of gripping and releasing the workpiece
2 An arm, which can move the hand in three planes
3 A wrist for the arm, with articulations that allow the hand/wrist assembly to be aimed anywhere in the workspace
4 Sufficient muscle power to lift a 500 pound (225 kilo) workpiece
5 Positioning repeatability to 0.3 mm
6 Manual controls, with which a person can operate all robot limb functions
7 A built-in memory which can learn the human teacher's instructions
8 Automatic systems which enable the memory to control operations in the absence of the human teacher
9 A speed of operation which is at least as fast as a person
10 A library of programs which can be selected at will, allowing the robot to be switched back to operations that it has been taught in the past
11 Facilities for safety and process interlocks with the plant or machinery that is to be operated
12 A computer compatible interface
13 Reliability of at least 400 hours MTBF (Mean Time Between Failure) in the actual working environment
14 Configuration which allows easy maintenance, with quick access and interchangeability of parts in the event of breakdown, aided by self-diagnostic routines

Figure 1.2 *Robot characteristics – extended specification*

Webster's Seventh New Collegiate Dictionary defines the robot as 'an automatic apparatus or device that performs functions ordinarily ascribed to human beings or operates with what appears to be almost human intelligence.'

The Robot Institute of America attempts to be more precise: 'a robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices, through variable programmed motions for the performance of a variety of tasks.'

One feature which a device must possess if it is to rank as a robot is the ability to operate automatically, on its own. This means that there must be inbuilt intelligence, or a programmable memory, or simply an arrangement of adjustable mechanisms that command manipulation. For these reasons, the following devices cannot be classed as robots, or part of the subject of robotics. They are listed here because, in many cases, they do share some of the technology that does apply to robots, and they are therefore related.

Prostheses: artificial replacements for parts of the human body. Limbs are of special interest, because they use servomechanisms and linkages to achieve movement and control to replace that of the missing or useless member, and some employ advanced electronics to amplify and harness body electrical impulses that were originally intended by Nature to stimulate human muscles.

Exoskeletons: frames which surround human limbs, or even the whole human frame, and which amplify the available power of the man or woman. They do not have intelligence or memory of their own, and so are not robots. In fact, it is most important that they cannot operate independently, since very accurate control and response times are absolutely essential to the safety of the user, who could easily damage himself or his surroundings in a badly designed system.

Telecherics: the name given to the subject of remote manipulators. These are used to add distance to the motions of a human limb, so that the operator can work outside the environment in which work has to be done. One obvious example is the range of devices used to handle radioactive materials. Once again, some of the linkage systems used may be similar to those used in some robots, but until the human operator has been replaced by some artificial intelligence, operating within a closed servo loop, manipulators are not robots.

Locomotive devices: imitate men or animals by walking on legs instead of the more usual mechanical method of wheels. The technology is very closely related to robotics, and to exoskeletal systems. A mobile robot is, of course, a locomotive device plus some form of built-in intelligence. Although experimental vehicles have been made, with up to eight legs, their intended advantages over wheeled or tracked vehicles for traversing rough, uneven ground have yet to be commercially proved.

These four classes of near relations are illustrated in Figure 1.3.

Robot cost *versus* human labor

At the beginning of this chapter, it was said that one of the most important factors which has paved the way for robots has been the changes in manufacturing methods to allow employment of unskilled people. In the interest of production efficiency, work has been broken down into a series of simple repetitive tasks that can be taught quickly. In fact, much factory work has been reduced to activities that are grossly subhuman, and there are few artisans to be found in modern manufacturing plants. This applies not only to the assembly line labor that Charlie Chaplin championed in his classic *Modern Times,* but also to fully automated machine stations, where the only human activities left are loading and unloading.

Charlie Chaplin's message was that unskilled and semiskilled workers were being exploited in subhuman work so that the United States' appetite for hard goods could be satisfied. In 1936, when *Modern Times* made its protest, labor was plentiful, cheap and more easily intimidated. The humane treatment and use of these human beings was

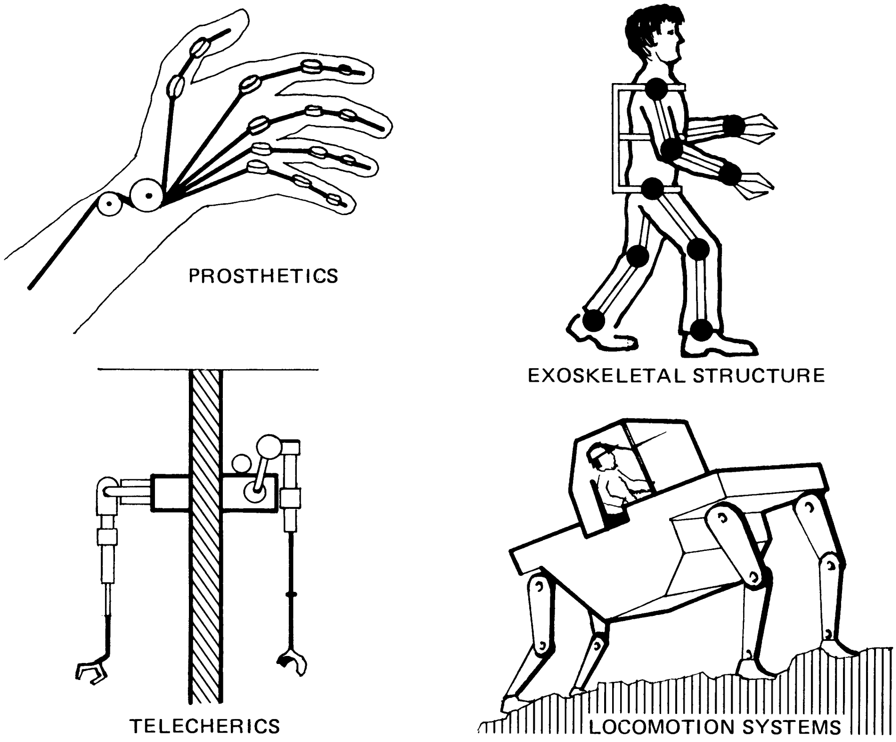


Figure 1.3 *Some near relations of robots*
The devices illustrated here have some technology in common with industrial robots. They cannot themselves be classed as robots, however, because none of these examples contains any inbuilt intelligence. These are certainly very sophisticated tools, but they are not able to work independently without constant directions from a human being.

a noble goal; but the captains of industry were motivated less strongly by noble goals than by the demand for profits. There was simply no economic justification or need to replace obedient and cost-effective human operatives with robots.

Many things have changed. A quarter of a century later, the demand for semi-skilled labor had increased. A semi-skilled factory laborer in the U.S.A. was costing $6,000 a year in pay and fringe benefits. In the automotive industry, this cost was destined to rise to $30,000 by 1979, and the trend continues: see Figure 1.4. The technique of designing work to eliminate skill had backfired. Workers demonstrated their aversion to dull, repetitive jobs by demanding high pay; higher even than that earned by workers in more skilled and more interesting jobs. Furthermore, turnover and absenteeism tended to follow job dissatisfaction, adding to the total cost of so-called cheap labor.

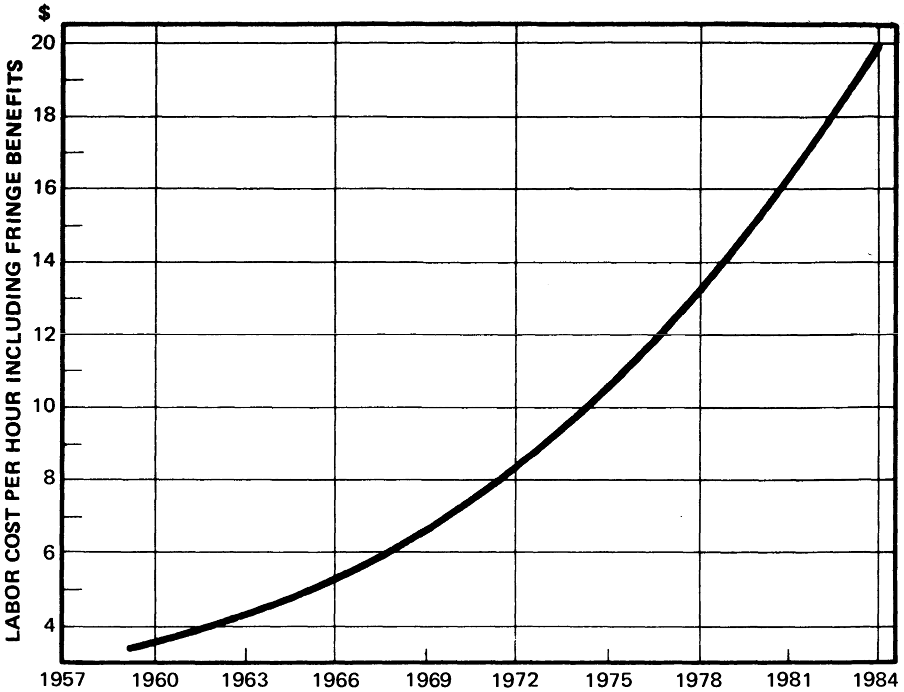


Figure 1.4 *Labor cost escalation in the U.S. automotive industry*
The trend of increased payments to workers continues, so that labor which was once regarded as cheap now has to be paid for at rates which compensate for the monotony and unpleasant nature of the job.

Economic and social factors governing the employment of labor are very much interdependent. These factors are discussed in later chapters when the advantages to be gained from introducing robots are evaluated. Several methods exist for analyzing the results of capital expenditure on new machinery and plant but, for the purposes of this chapter, one simple approach (the payback method) is sufficient to demonstrate that the economic viability of industrial robots is a fact. Not only are robots possible to make – they have become an economic alternative to human labor.

Payback analysis

Suppose that a human operator must be paid $24,000 a year in wages and other benefits to do a particular job that could be done, instead, by a robot. Suppose also (for simplicity in this case) that the robot would produce the same rate of output as the human, per shift. The useful working life of this robot is going to be at least eight years, but a payback period of under three years is normally sought by accountants. The robot and its accessories are going to cost $55,000, and the annual maintenance costs have been demonstrated to be $3000. One other important factor is that the robot would be capable of working more than one shift, so that it could in fact replace at least two men.

Payback formula $P = \frac{I}{L - E}$

where
P = the payback period, in years
I = the total capital investment required in robot and accessories
L = total annual labor costs replaced by the robot
E = maintenance costs for the robot

Calculation for one shift working
I = $55,000
L = $24,000
E = $ 3,000

Period $= \frac{55,000}{24,000 - 3,000}$ or 2.62 years

For two shift working
L becomes $48,000 and
E rises to $5,000

The payback period reduces to
$\frac{55,000}{48,000 - 5,000}$ or 1.28 years

Figure 1.5 *Payback evaluation of robot costs*
Application of the simple payback formula demonstrates that robots can be viable in replacing expensive human labor. The cost benefits are seen to be even greater when two shift working is in operation, in this example reducing the payback period from 2.62 to only 1.28 years.

The calculations are displayed in Figure 1.5. For one shift operation, the payback period works out at 2.62 years. If the robot is utilized more fully, over two daily shifts, the payback period drops to only 1.28 years. This result is likely to satisfy even the most critical accountant. The figures become even more impressive when it is realized that the effective working life of industrial robots can be more than eight years, based on actual operating experience, and that they can work three shifts right round the clock.

Die casting – an early success story for industrial robots

The following example dramatizes the potential in robot application. The process of die casting is carried out to produce accurate, well finished workpieces by the high pressure injection of molten metal into an accurately machined steel die. The most typical metals used are zinc, aluminium, and their associated alloys. The process is described in detail in chapter 10, but here is a brief summary of the process.

The die consists of two separable, mating halves. Before use, all residue from the previous casting operation has to be cleaned off, and then both halves must be lubricated. A press brings the die halves together, and the charge is injected under high pressure. Pressure is maintained for a period sufficient to ensure that the die has been completely filled. The pressure of the charge results in a slight escape of metal through the mating die surfaces, which has the appearance of thin fins projecting from the workpiece when it is first removed from the die. These protrusions are called 'flash'.

It is necessary to water-cool the die and its contents to solidify the molten metal. Once the metal has solidified, the press opens the die halves and the casting can be removed. The die casting usually needs further cooling in a quench tank, and then the flash must be removed. This is done in a trim press.

Automating the die casting process

Die casting can be an unpleasant occupation for human operatives, combining tedium, heat, noxious fumes, and other undesirable problems in the working conditions with actual physical danger. In common with many other industrial processes, output rate, product quality and the amount of scrap produced all depend to a large extent on the skill of the individual operator. Die casting has, perhaps, more than its fair share of operational variables, ranging from the chemical and physical state of the hot metal, through mold treatment, machine adjustment, cycle timing and the physical and mental condition of the human operative at any given time.

Most die casting shops have to handle small batch quantities of workpieces. Generally speaking, any attempt at special purpose automation would prove to be prohibitively expensive in such circumstances. To overcome many of the variables associated with human operation, some sort of automation is desirable. But this has to be flexible. It must be possible to set up new process programs easily and cheaply as each new batch is loaded. Better still, when a repeat batch is needed in the future, it should be possible to recall the appropriate program from a memory, rather than have to start programming all over again. This is the sort of flexible automation that industrial robots can provide, and this is one of the reasons why die casting was an early commercial success story for robotics. It was, in fact, the very first task taken on by a robot, as far back as 1961.

Robotized die casting

Robots can be used at any stage of the die casting process, or in trim press operation. Some applications are suitable for complete systemization, with one or more robots handling all operations from the start of the die casting machine cycle to stacking trimmed castings. In this instance a straightforward one press-one robot set-up serves to illustrate the flexible automation that robots can provide.

Picture the robotized press. In place of the human operator stands the robot, with its single, powerful arm. This arm can be extended or retracted, raised or lowered, and it can be swivelled from side to side. At the end of the arm is a mechanical wrist which can also be swivelled. Attached to the wrist is a hand capable of grasping the workpiece. A control panel on the robot body is supplemented by a pendant control box, from which a human operator can control the movements of robot arm, wrist and hand. The pendant fits neatly into the man's hand. All the pendant controls are designed logically, to produce robot movements that correspond with the directions in which the control knobs are themselves moved.

The robot is able to record each instruction from its operator in a stored program. The control unit has provision for interlocks between the robot and the machine which it is going to operate. These interlocks are essential and ensure that no part of the production cycle can be initiated before the previous process stage has been satisfactorily completed. This system of feedback from machine to robot depends on limit switches and other sensors that can pick up the travel or positions of moving parts. For example, the travel of the injection piston can be used to provide indication that the mold has been completely filled. An infra-red detector senses the presence of a hot die casting in the robot hand; absence of sufficient heat radiation would signal that all or part of the workpiece had been left in the die.

In many respects the electrical links, interlocks, limit switches, temperature sensors and their associated circuitry resemble those used in special purpose automation controls. There are, however, essential differences. The set-up or teaching time is far simpler and quicker using a robot. And all these process controls are fitted to standard, general purpose machinery. When one batch of die castings has been finished, another pair of different dies can be used in the same die casting machine, using all the same equipment and controls. True, the robot program has to be changed, but this is either accomplished by a simple reteaching operation, or by re-using a previous program that has been stored on a tape cassette. Had this all been a special purpose, custom built machine, the whole investment would have to be written off when the product run finished.

Summarizing, we have a general purpose die casting machine, operated by a single armed robot equipped with teaching controls and a memory. There are logic links between the robot and the machine, and a human operator can be called upon to carry out initial robot instruction. The usual noise, heat and fumes are there too, but the man knows he can get right out of there just as soon as he has taught the robot to make die castings. The robot memory ensures that the robot will carry out every operation for hour after hour, shift after shift, without fatigue and without variation. Robot users have reported significant reductions in scrap and reject rates. Machine utilization rates are increased – one typical user reporting 25 per cent. Removing the man from the immediate operational vicinity means reduced needs for safety equipment, with consequent savings in costs. And there are obviously dramatic reductions in labor costs, because there is no longer any need for an operator to be kept fully occupied at the machine. All of these advantages add up to a powerful argument for robotization.

Robots *versus* special-purpose automation

It is not enough to compare the robot with its human counterpart. Long before our technological resources permitted the development of an industrial robot, we had produced automatic machinery that was capable of mass-producing many of the products which are in broad commercial and consumer use. For example, there are machines that make bottles and other machines that fill and cap these bottles. There are machines that automatically manufacture our light bulbs. And, there are machines called transfer machines that can ingest a raw casting and deliver a completely machined engine block. All of this equipment has come to be lumped together as automation.

It is reasonable to conclude that robotics is no more than a subclass of automation and, certainly, today the production of robots is an almost negligible percentage of industry's total expenditure for automation equipment. However, there is something about the robot mystique that singles out robotics for special attention. As robots become ever more sophisticated, the distinction will become more dramatic.

A robot that can boast of eyesight and tactile sensing will certainly be better at emulating a human operator. And, the robot carrying out its tasks in anthropomorphic fashion reminiscent of a human worker is certainly distinct from an aggregation of mechanisms specially designed to produce one or another specific product.

We have noted that the prime advantage a robot has over human labor is economic. But the robot also has advantages over special-purpose automation. In fact, the robot increases its niche in industry by driving a wedge in between manual labor and special-purpose or 'hard' automation.

The robot can take over from human operators because its flexibility permits it to accomplish tasks that are not readily accomplished by special-purpose automation. It is axiomatic, of course, that these activities are done more economically by robots than they would have been done by humans. But how is it that a robot can also intrude on activities that might be suitable for hard automation? The answer is that an industrial robot provides three unique benefits when compared to hard automation.

1 Reaction time: a sufficiently flexible and sophisticated industrial robot is 'off-the-shelf' automation. Such robots, by definition, are manufactured for stock and not to special purpose order. They are poised and ready to go.

Evidently, when a decision is made to automate, the financial benefit does not start until the automation is operating. Thus, fast reaction time provides a cost saving which must be credited to the industrial robot when comparing investment with the cost of special purpose automation.

Consider the example of the automobile manufacturer who, through the use of industrial robots, was able to design the automated assembly line concurrently with the design of the vehicle itself.

The ability to shorten the cycle time for introduction of new models is most highly valued by the automobile industry.

There is another type of reaction time benefit to be derived from an easily taught industrial robot. One U.S. job shop diecaster with 16 Unimates tells how important rapid programming is when short runs are the rule. And, how convenient it is to touch up programming virtually on the fly to compensate for process variability such as die deterioration.

2 Debugging: when literally millions of dollars are spent in design of a sophisticated industrial robot slated for replication by the hundreds (perhaps by the thousands), the debugging investment is on a comparable scale. Such fastidious testing and field trial is economically impractical for special purpose automation. The experience of General Motors in Lordstown bears this out. Twenty-six Unimates went to work there amidst grave misgivings regarding the electronic-hydraulic sophistication of this equipment. But the real debugging anguish came in getting the conventional automation on stream — all those simple indexing devices, solenoids, actuators and clamping mechanisms that are the legacy of special purpose assembly systems; those single purpose elements whose debugging in a system occurs on the production floor, after delivery.

The more flexible the industrial robot, the smaller the percentage of a system that must be purpose built and the lower the debugging cost becomes. This principle applies right down to individual work stations. If manipulative power is limited, it usually is paid for by additional set up cost, equipment moving cost and lost time.

3 Resistance to obsolescence: the essence of robotics is to provide a form of automation which is immune to obsolescence. A proper industrial robot is neither product, nor operations, nor industry limited. The experience of Unimation Inc. proves the point. With thousands of machines in the field, some having worked for 15 years accumulating over 90,000 hours in production, there is still no sign of technological obsolescence. Unimates get overhauled, they get new job assignments, they get sold in an after-market, but they do not get scrapped. Model change has not embarrassed the Unimates in the field to date and there are no ominous signs.

Chapter 2

Robot anatomy

Robot capabilities range from very simple repetitive point-to-point motions to extremely versatile movements that can be controlled and sequenced by a computer as apart of a complete, integrated manufacturing system. It would be convenient if all robots could be placed into neat categories, each category being labelled with all the job capabilities belonging to its robot members. Although this can, and will, be attempted here, there are dangers and pitfalls in trying to establish a rigid robot classification. The real problems result from the fact that, while a simple robot might be perfectly capable of doing a good job in a plant, a more sophisticated (and therefore more expensive) robot could possibly do the job even better, and even more profitably. Classification itself is not too easy, since robot design development progress has caused a good deal of overlap between what were once clearly distinguishable robot types. Rather than be defeated by these arguments, we can first consider three simple robot categories, and then go on to look at the complications introduced by variations in anatomical conformation and different designers' preferences in matters of drive mechanisms and control techniques.

Robot classification

All robots consist of two major component systems. First, there are the moving parts, chiefly comprising the arm, wrist and hand elements. This is the most obvious part of the robot to an outside observer. The moving system is often referred to as the manipulator, but this term can be misleading, because it is easily confused with one of the robots' near relations, the telecheric device (see Chapter 1).

Complementary to the moving robot system is the control system. At its very simplest, this might consist only of a series of adjustable mechanical stops or limit switches. At the other extreme are the computer type controls, which give the robot a programmable memory, which allow the robot drives to follow a path that is accurately defined all along its length by a series of continuous coordinates, and which can also be coupled with another computer or machine control system to synchronize the robot for the most efficient and safe production operation possible.

Comparison between any two robots that belong, broadly speaking, to one of the three categories listed below could easily reveal that quite different drive systems had been employed to achieve roughly the same ends. Control systems are likely to correspond more closely between robots in the same category. Discussion of different drives and control possibilities follows later in this chapter.

Limited sequence robots

As its name implies, a limited sequence robot is at the least sophisticated end of the robot scale. Typically, these robots use a system of mechanical stops and limit switches to control the movements of arm and hand. Operation sequences can often be set up by means of adjustable plugboards, which are themselves associated with electromechanical switching. By electromechanical switching is meant a combination of relays and rotary or stepping switches. As a result of this kind of control, only the end positions of robot limbs can be specified and controlled. The arm, for example, can be taken from point *A* to point *B*, but the path in between is not defined. Thus, the controls simply switch the drives on and off at the ends of travel. This mode of operation has earned such machines the nicknames of 'pick and place' robots or, perhaps impolitely, bang-bang machines.

Figure 2.1 is a block schematic diagram of a limited sequence robot. The drive mechanism could be electrical, pneumatic or hydraulic. Most robots of this type are small, and tend to move faster than their bigger, more complicated brothers. The use of mechanical stops and limit switches gives good positional accuracy, which is typically repeatable to better than ±0.5 mm. Purchase price is around 25%-50% of that required for bigger robots. They have been used successfully in a variety of applications, including die-casting, press loading, plastics molding and as part of special-purpose automation. Disadvantages, other than the obvious control limitations, are that the number of limb articulations is likely to be few, and setting the machine up is more time consuming and tedious than for those with better control systems. The number of movements possible in a total production sequence must be limited to the number of limit switches, stops, and programmable switches contained by the robot. Such robots are not 'taught' to perform their job, but have to be set up in the same way as an automatic machine would be adjusted. There is no memory unit as such, other than that embodied in the settings of the plug board and all the mechanical stops.

Unlike robots in the other categories, the simple limited sequence control system cannot exercise any real control over the limbs while they are actually in motion. It is possible to provide more than one stopping point along each path, but the primitive nature of the memory

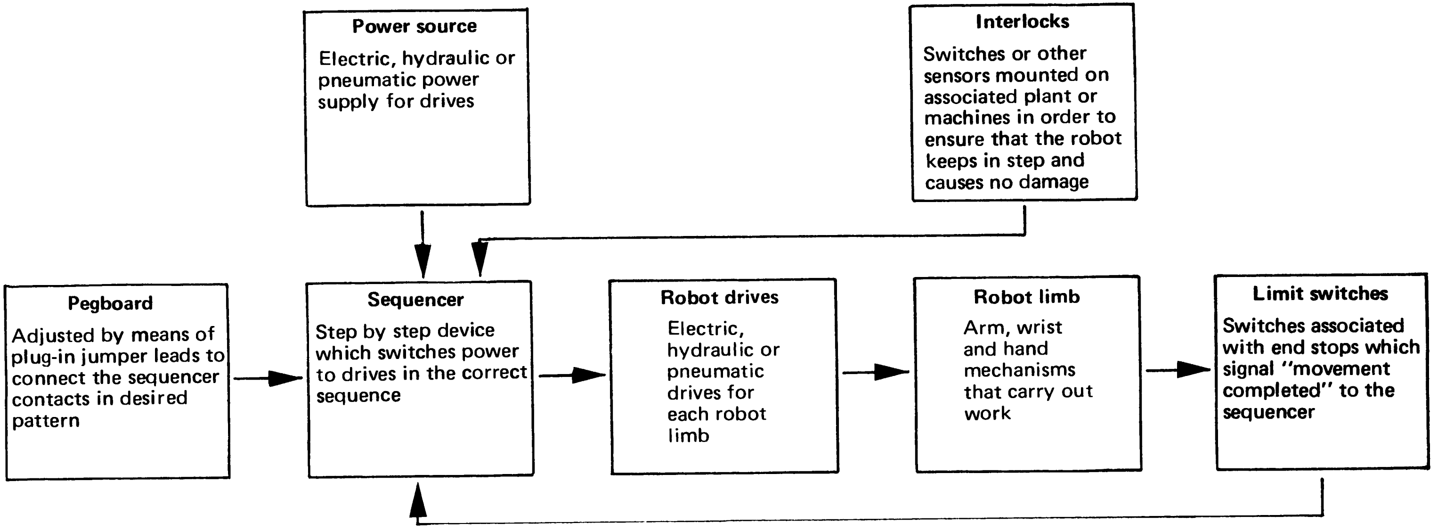


Figure 2.1 *Schematic arrangement of a typical limited sequence robot*
The program sequence is predetermined by arranging plug-in jumper leads in an appropriate pegboard pattern. Each robot limb movement is set to start and stop by means of adjustable end stops. Limit switches at each of the end stops operate to inform the sequencer that particular movements have been completed. The sequencer, controlled by signals from the limit switches, rotates step by step to supply power to each robot drive according to the requirements of the production operation. Interlock switches on the operated machine and other associated plant ensure that the robot is kept in step with the manufacturing cycle, and prevent the robot from disgracing itself by causing accident or damage by collision.

system restricts the number of these for practical purposes. In this type of machine the motion of the working arm is often extremely limited also, as are the number of available degrees of freedom. In fact, with such simple machines, options such as wrist and hand movements and arm rotations are provided to meet the needs of specific customers.

Programming limited sequence robots is usually accomplished by setting up all the end stops in their appropriate positions, and by adjusting contacts in the sequencing unit so that all the steps take place in the correct order. A peg board is often used to make the task of sequencing quicker.

Here is a description of a limited sequence device in operation. When a sequence is to be started, the controller has to switch power to the relevant drive motor. If the drives are electric, then the controller will probably close a relay to switch the current through. Where the drives are hydraulic or pneumatic, then appropriate solenoid valves are operated. The motion generated by the drive normally continues until the moving limb is physically restrained by hitting an end stop, the physical shock being cushioned by some form of shock absorbing device. Thus there are only two positions at which the moving part can come to rest, one at the beginning and the other at the end of a programmed move. Obviously, the system is arranged so that a limit switch cuts off the motive power as soon as the end stop is reached. When the initial movement has been finished, the limit switch not only cuts off the drive power, but it also signals the controller that the particular movement has been finished, so that the next movement can start.

The controller is a sequencing or stepping switch. It could be a set of contacts operated by cams on a spindle which can be rotated in steps of a few degrees at a time by a small electric motor. Each time the sequencer receives its own drive signal, it steps to its next position, and so switches drive power on or off to a particular part of the robot. This performance is repeated, step by step, until the whole program has been carried out, the manufacturing cycle is complete, and the robot is ready to start all over again on another cycle.

So far so good. But how does the controller ensure that the robot doesn't put its arm into the closing jaws of a press, or try to load a workpiece into a spinning chuck? The robot cannot see the machine it is trying to operate. There are no robot senses equivalent to those of a human operator. Some method has to be found to make the robot aware of the real world around it. This is accomplished by providing additional limit switches or other electrical sensing devices on the machine to be operated. These are connected to the controller to provide additional signals to the sequencer, complementary to those obtained from the switches mounted on the robot itself. Robot limb movements are therefore carefully interlocked with the machine being operated. This prevents the robot from trying to commit suicide, avoids collision damage to associated plant, and enables the robot to carry out its operations not only in the correct sequence, but also at the appropriate moments in time.

Playback robots – with point-to-point control

One characteristic of limited sequence robots is that they are generally difficult to reprogram. This arises from the nature of the control system and memory, which are all embodied in a complex and interdependent set of limit switches, interlocks, end stops and electrical connections. Not only does this kind of electromechanical arrangement prove tedious to change, but it also limits the number of different sequence steps that can be accommodated practicably within the control system.

Another method for achieving positional control of each limb relies on the provision of some form of servo mechanism. Figure 2.2 illustrates the principle in simple diagrammatic form. Each movable robot limb is fitted with a device that produces an electrical signal, the value of which is proportional to the limb position. The system is arranged so that the direction of drive travel is such as to reduce the positional error (obviously), and as the limb moves closer to the desired position, the error signal automatically reduces until it reaches zero, and the limb stops in the correct position. This is analog control, and in practice calls for a high degree of engineering skill in design to achieve satisfactory positional accuracy, and freedom from oscillation.

If a knob is provided on a control panel which can vary the command signal for a particular limb, then that limb will move as the knob is moved. Thus, a form of remote control is achieved, and the control panel can be given as many knobs as there are limbs to provide a man with the means for operating the robot.

The device described so far is a manipulator, and not a robot. A memory unit has to be added to complete the control unit before it can properly be called a robot and earn its place rightfully in this book. Once the memory unit exists, a very flexible robot results. The position of the limbs at each operational step, and the total operational sequence are all recorded in the memory. The memory is then used to stimulate all the servo systems. The procedure for setting up such a robot is far easier than for a limited sequence robot. It is only necessary to use the controls to drive the robot limbs to the required position for each operational step, and then to record the exact condition of the robot in the memory by the simple act of pushing a button before proceeding to drive the robot to the next step in the sequence. In other words, the robot can be taught, by simply driving it through all stages of the operation.

For obvious reasons, a robot which can be taught in this manner is sometimes known as a playback robot. It is still essential to provide

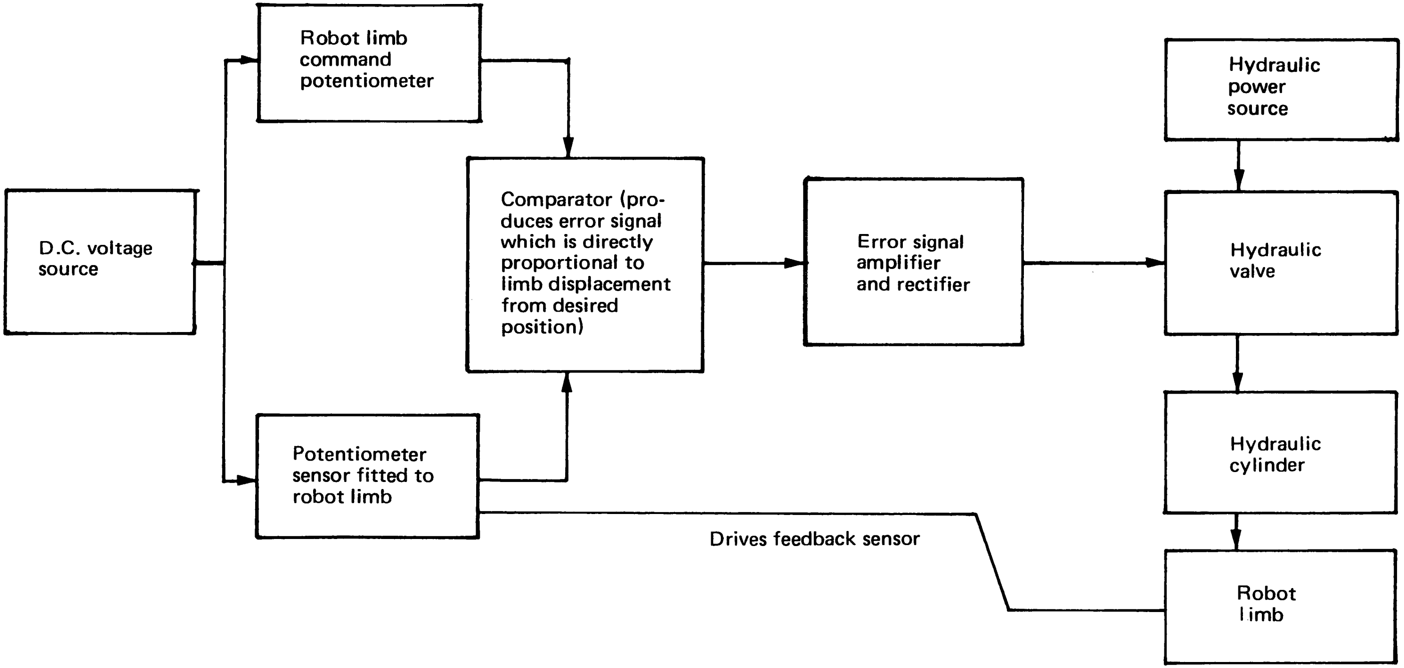


Figure 2.2 *Analog servo system*
This diagram illustrates one conventional way to achieve positional control of a robot limb.

safety and control interlocks between the robot control unit and the machinery being operated, to prevent collisions and other problems. Not only is the robot far easier to set up than a limited sequence robot, but the memory unit is able to take advantage of modern technology by digitizing all of the command position data. This means that the robot is able to remember a large number of steps.

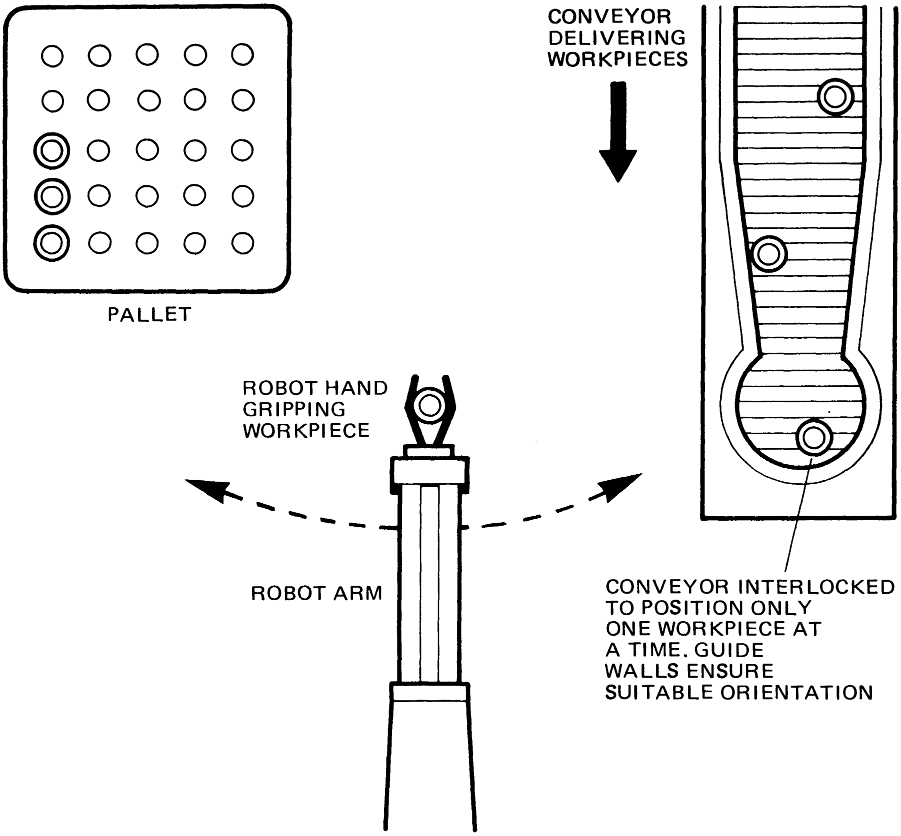


Figure 2.3 *Task for a playback robot with point-to-point control*
In this example, the robot is required to pick up cyclinders from the end of a conveyor system, and transfer them one at a time to the pallet. The conveyor is specially equipped with side wall guides and a photoelectric interlock to ensure that cylinders arrive at the pickup point singly and upright.

The problem set out in Figure 2.3 serves to illustrate the operation of a playback robot capable of point-to-point control. The robot is required to pick up cylinders from the end of a conveyor, and load them on a pallet fitted with 25 spindles. A photoelectric control on the conveyor ensures that the conveyor stops as soon as a cylinder has been delivered to the pickup point. Otherwise, there could be a log jam which might confuse the blind robot. Guide walls coax the cylinders into a well-defined area, so that the robot can always be certain of finding a cylinder in the same place, and in the same attitude (standing on one end). Location of the pallet is also important, and this is arranged on a table provided with locating lugs. When the full pallet is eventually removed and replaced with an empty one, these lugs position the new pallet accurately in the same position occupied by its predecessor. Although the robot is always going to pick up cylinders from one point, it is being asked to set them down in a sequence of 25 different locations, one for each spindle on the pallet. A problem of this size demands a robot memory far greater than that embodied in the electromechanical control unit of a limited sequence device.

Figure 2.4 is a diagrammatic representation of the robot to be used

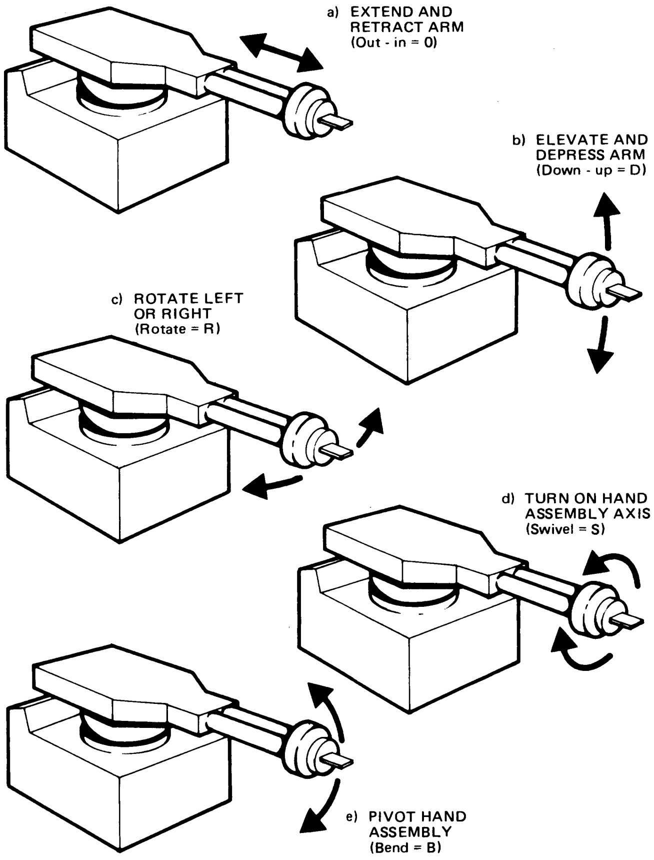


Figure 2.4 *Typical articulations of a playback robot with point-to-point control*
There are five articulations in this case, all of which are programmable.

for this job. The human operator will lead the robot through all the steps of the operation, one simple step at a time, recording each move in the robot memory as he goes. To make his job safer and easier, the robot can be switched to a special 'teach' mode during this process, which reduces the robot's operation speeds, and gives full command of all robot movements to the teacher. The operator is provided with a control panel mounted on a pendant cable, which allows him to stand in the most favorable position for observing and controlling the action. One of these teach pendants is illustrated in Figure 2.5.

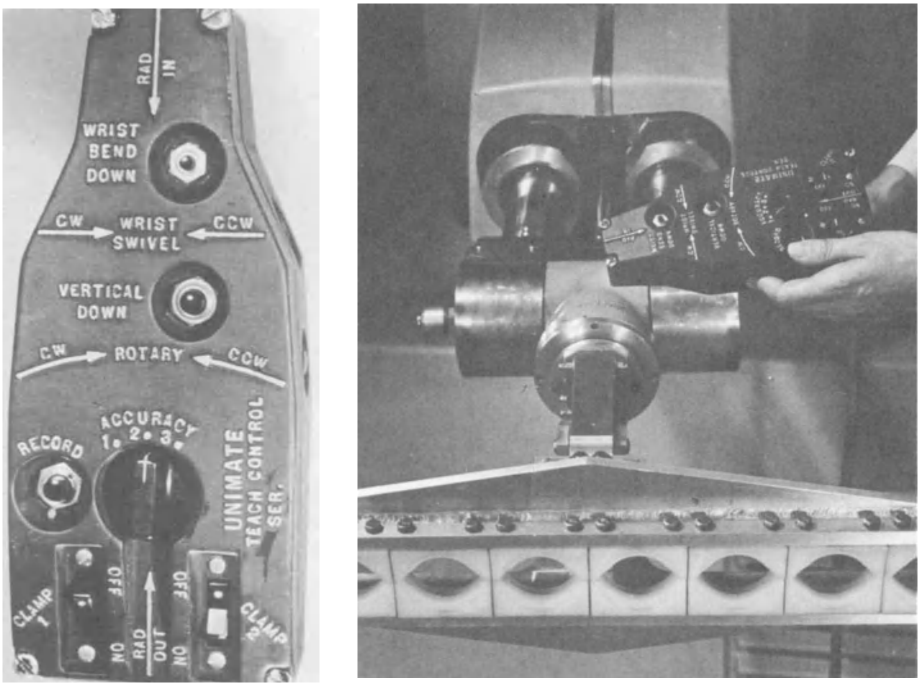


Figure 2.5 *Teach pendant for instructing playback robot with point-to-point control* This is a pendant control unit which can be held in the hand by a human operator while he takes a robot through its learning process.

There are many variations in the approach to positional control with different limb position sensors and different power sources. For any servo system chosen, dynamic performance demands are harsh. No matter what the arm attitude or its load, high-speed and critical damping are urgently required.

In order to prevent the robot from taking an inappropriate action two interlock switches are essential. One of these is arranged at the pallet, to prevent the robot from trying to load cylinders before an empty pallet has been put into place. The other interlock is taken from the same photoelectric device which controls the conveyor. Just as it is essential to stop the conveyor from depositing further cylinders at the pickup point as long as a cylinder is at that position, so it is necessary to stop the robot from attempting a pickup when no cylinder awaits it. Otherwise, we should be able to observe the spectacle of the robot grabbing at thin air, and trying to deposit an imaginary cylinder onto the pallet.

The operator must arrange for a cylinder to arrive at the pickup point, and he has to ensure that this is in the correct vertical attitude. Using the pendant controls, and with the robot switched to the teach mode, the training process now proceeds, step by step, as follows:

1 Move the robot arm until the gripper is just above the cylinder to be picked up, with the hand open.
2 Rotate the hand and wrist controls as necessary to align the grippers level, in a horizontal plane.
3 Record the robot attitude by pressing the 'record' button.
4 Lower the arm until the grippers surround the cylinder. Carry out fine adjust until the grippers are level, and symmetrical about the cylinder.
5 Press the record button.
6 Close the hand, so that the cylinder is gripped.
7 Press the record button.
8 Raise the arm well clear of the conveyor, so that it is above the height of any obstructions between the conveyor and the pallet.
9 Record.
10 Swivel the robot and adjust the arm extension until the cylinder is positioned approximately above the first peg on the pallet.
11 Record.
12 Lower the arm carefully until the hole in the cylinder is just above, but not touching, the first peg in the pallet. Ensure that the cylinder is held vertically, and if necessary, adjust the hand, wrist and arm controls to achieve this.
13 Record.
14 Lower the arm until the cylinder rests on the pallet.
15 Record.
16 Open the robot hand.
17 Record.
18 Raise the robot arm clear of all obstructions.
19 Record.
20 Repeat this operation for all remaining cylinders, until the pallet has been filled.
21 Replace the pallet with an empty one, switch the robot to normal operational mode, switch on the conveyor, push the robot start button, and watch the action.

Provided the interlocks have been correctly set, and given a regular flow of cylinders along the conveyor, the robot should now proceed to carry out the filling of the pallet in a regular, reliable and untiring manner. The robot will be seen to stop momentarily at each of the positions where the record button was pressed during the teaching session.

It is well to realize exactly how the robot motion operates. When the robot is commanded to move from one position to another, this could involve independent operation of two or more of its articulations. The only information which the robot has been taught concerns the attitude of all limbs at the start of the move, and the new attitude of those limbs when the particular move has been finished. While making the move as fast as it can, and while moving all limbs simultaneously to fulfill the given command, there is no definition of the paths which the robot limbs will trace. In other words, the control is point-to-point, as the name of this class of robots indicates. This is why it was necessary for the operator to record some of the intermediate robot positions in this example. If step 8 had not been recorded, for example, the robot arm could have clouted any obstruction between the conveyor and the pallet. Steps 10 and 12 were recorded to prevent the robot arm coming in obliquely to the pallet, which would have caused the cylinder to strike the pallet pin at an awkward angle, thus causing general mayhem. Each vital turning point in the robot trajectory must be recorded in a point-to-point control system.

Robots with point-to-point control operating on a digital basis may have virtually unlimited memory. In the example just described, the human teacher has programmed in nine separate record points for each cylinder to be handled. This amounts to 225 recorded steps for all 25 cylinders. Point-to-point robots are obviously capable of doing any job performed by a limited sequence robot. Presuming that their memory capacity is sufficient, they are also capable of more sophisticated jobs such as palletizing, stacking, spot welding and the like.

Playback robots – with continuous path control

There are, of course, applications in manufacturing industry where it is necessary to control not only the start and finish points of each robotized step, but also the path traced by the robot hand as it travels between these two extremes. A good example of this requirement is provided by seam welding, where a robot is asked to wield a welding gun, and move it along some complex contour at the correct speed to produce a strong and neat weld. One way of looking at this problem is to regard continuous path control as a logical extension of point-to-point control. It is feasible to provide a robot with a memory that is sufficiently large to allow path control that is, to all intents and purposes, continuous.

Alternately, the continuous path robot may be taught in real time. The operator takes hold of the robot by its hand, and leads it through the motions that it is going to have to perform by itself. The operator tries to copy the speed of travel required. During this teaching process, the robot has to record the movement and hand attitudes continuously, or approximately continuously, in its memory. This is achieved by giving the robot an internal timing system, which for example, could be synchronized with the 60 Hz main supply frequency. Using this time reference, the robot's movements are sampled at the rate of 60 times each second, with the results being committed to memory. Even at this sampling speed, a large amount of data has to be accumulated in the memory. Consequently, the storage systems for continuous path robots of this type often are magnetic tape units.

To increase the operational usefulness of continuous path robots, provision is usually made for the playback speed of operation to be different from the teaching speed. This is a great help to the operator, because in some applications the actual speed of travel is very slow, and the operator finds it easier to teach the robot at a faster speed, where he can make a smoother run, free from handshake. The converse is obviously also true. For higher speed continuous path programs as in applying a bead of sealant, it may be preferable to program at a lower than playback speed.

Arm geometry

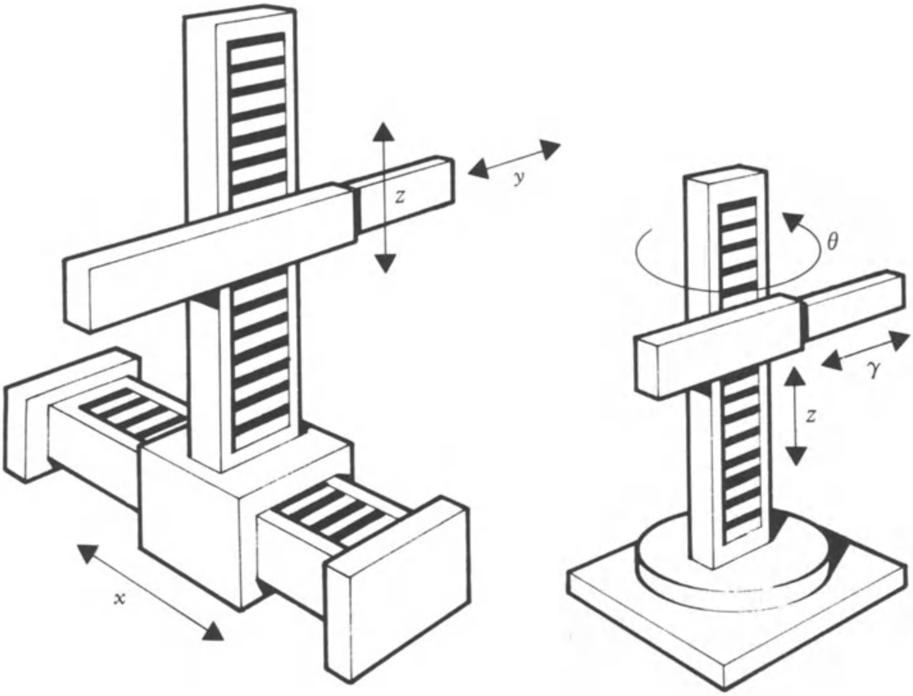
A robot must be able to reach work pieces and tools. This requires a combination of an arm and a wrist subassembly, plus a hand, commonly called an end effector. The robot's sphere of influence is based upon the volume into which the robot's arm can deliver the wrist subassembly. A variety of geometric configurations have been studied and tried and their relative kinematic capabilities appraised. So far, robot manufacturers have selected one or more of the following:

○ Cartesian coordinates
○ Cylindrical coordinates
○ Polar coordinates
○ Revolute coordinates

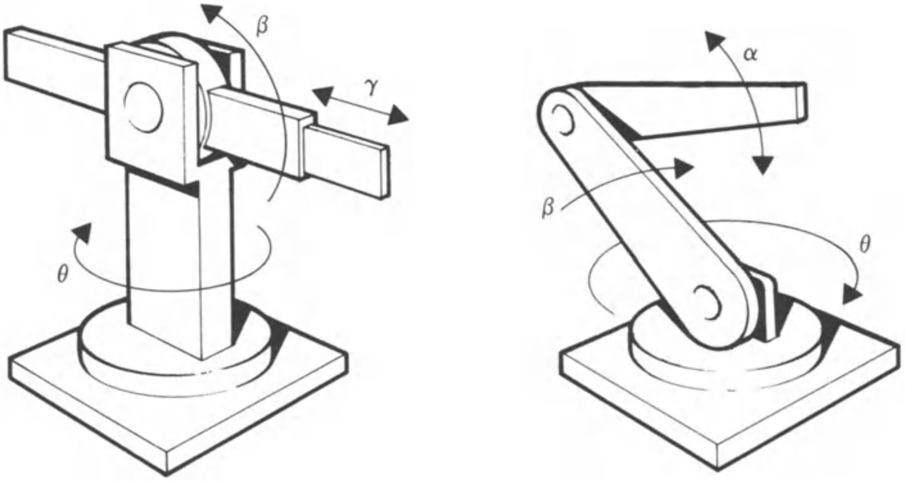
Sketches of some typical embodiments are shown in Figure 2.6.

Evidently, each of these configurations offers a different shape to its sphere of influence, the total volume of which depends upon arm link lengths. For different applications, different configurations may be appropriate. A revolute arm might be best for reaching into a tub, while a cylindrical arm might be 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



CARTESIAN COORDINATES CYLINDRICAL COORDINATES



POLAR COORDINATES REVOLUTE COORDINATES

Figure 2.6 *Robot arm configurations* effector as demanded by workpiece placement. Commonly, the wrist provides three articulations that offer motions labeled pitch, yaw and roll – an obvious analogy with aircraft terminology. Figure 2.7 is a typical execution.

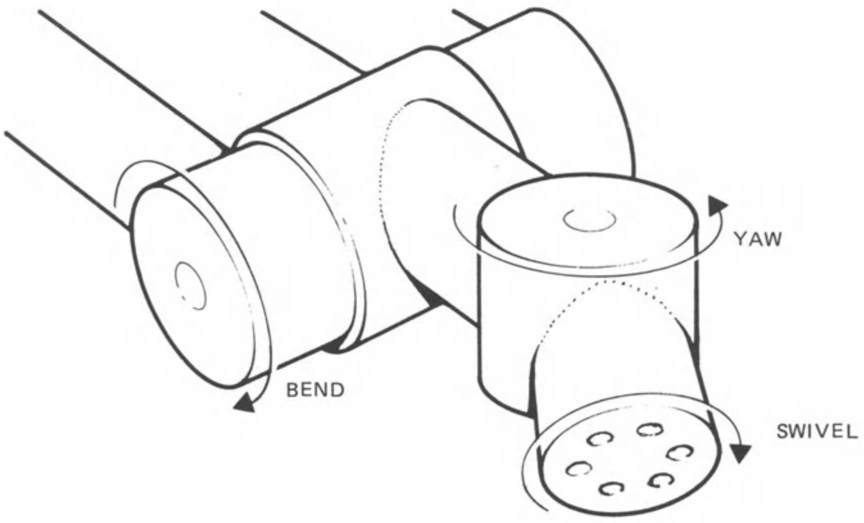


Figure 2.7 *Typical wrist articulations*

It may be noted that any of the arm coordinate systems requires three articulations to deliver the wrist assembly anywhere in the sphere of influence. It then requires three more articulations in the wrist for universal orientation of the end effector.

Quite often, robots are able to cope with job assignments without employing a full set of six articulations. This arises out of some symmetry in either the workpiece or the work place layout. For example, to move a bowling ball around in the sphere of influence requires only three articulations, because a ball is always oriented, irrespective of a gripper's orientation. More frequently, parts have one axis of symmetry (i.e. cylindrical) and this allows the robot arm to degenerate to five articulations.

Actually, five articulations are quite often adequate when the workplace is arranged to reduce part-manipulation needs. This happens, for example, when the beds of machine tools are all located parallel to one axis of a cartesian coordinate robot or on a radius of base rotation for cylindrical, polar or revolute robot arms.

Some might say that this compromising of number of articulations is begging the question of robots versus special-purpose automation. The robot should be the universal solution, readily transferred to other applications. In this vein, reference should be made to the elegance of computer control of robot arms. Given a six articulation arm of any configuration, software can permit a program to be generated in cartesian coordinates irrespective of the choice of articulations. Indeed, the software can be powerful enough to think only in tool coordinates. That is, the programmer concerns himself only with the tool on the end of the robot arm. He can think in terms of the tool's frame of reference and computer subroutines automatically make the various articulations move so as to accomplish the desired tool manipulation.

With computer control, the robot's geometry tends to lose installation significance. The engineering execution becomes the abiding issue.

Drive systems

A drive system is required for each robot articulation. In addition to driving the arm, the hand and the wrist, most types of grippers also need a drive mechanism for the functions of holding and releasing. Robot drives can be electrical, pneumatic, hydraulic or some combination of these.

Pneumatic systems are found in about 30% of robots, although they are confined mainly to the limited sequence devices. Pneumatic drives have the merit of being cheaper than other methods, and their inherent reliability means that maintenance costs can be kept down (although other types have also become reliable through progressive development). Since machine shops typically have compressed air lines available throughout their working areas, this makes the pneumatically driven robot a more familiar tool to shop personnel. Unfortunately, the system does not make for easy control of either speed or position, two essential ingredients for any successful robot.

Electromechanical drives are used in some 20% of robots. Typical forms are servomotors, stepping motors, pulse motors, linear solenoid and rotational solenoids. But the most popular form of drive system is hydraulic, because hydraulic cylinders and motors are compact, and allow high levels of force and power, together with accurate control. A more detailed comparison of the advantages and disadvantages between electrical and hydraulic drives is worth consideration.

Hydraulic versus *electric drives*

Hydraulic drives can be divided into actuators and motors. Actuators can be linear piston actuators or rotary vane actuators. Among the hydraulic motors there is a choice of piston, gear, vane and ball configurations. The choice is determined by several factors, such as the application, whether the motion required is linear or rotary, performance, requirement of lock-up, cost, reliability, and so on. The best choice is generally the simplest device that will do the job satisfactorily. Of all the hydraulic drives, the piston actuator is simple, very reliable, and the least expensive.

If better dynamic performance is necessary, the choice lies between making the piston actuators greatly oversized, or switching to hydraulic motors. Motors usually provide a more efficient way of using energy to achieve a better performance, but they are more expensive. Not only is the cost of hydraulic motors several times that of the actuators, ut they also need auxiliary devices such as gearing or ball screws to complete the system. Whichever system is chosen, an electro-hydraulic servo valve is required.

Most electrical drives of robots are today in the form of rotational motors. Like the hydraulic motors, they need either gearing or ball screws to provide a complete actuation system. In the electrical system, the electro-hydraulic servo valve is replaced by a servo power amplifier.

It is seen that while electrical and hydraulic motor drives are approximately equal in complexity, hydraulic actuators are considerably simpler. The only drawback to the actuator solution is its lower stiffness. The question is, therefore, are motor drives for robots necessary? More often than not, the answer is no. Compare with machine tools that have natural structural frequencies in excess of 50 Hz – essential for them if they are to be chatter-free and effective chip producers.

Robots also need stiff structures and drives to be effective manufacturing tools, but on a different level. Few, if any, robots have a resonant frequency above 10 Hz. Machine tools are slow moving in relation to robots. The robot cannot afford fat to achieve stiffness. It needs rigid, but light, structures that can be adequately actuated by a piston cylinder rather than a bridge builder's dream moved by a screw.

The motor driven robot will have a much higher maintenance cost than the simpler actuator driven robots, not only because of the many more and costlier components, but because of localized wear in gears and ball screw by fretting corrosion during active servoing.

Fifteen to twenty years ago some machine tool builders switched from hydraulic to electrical drives. The reason behind the switch was believed to be reliability and the leakage problems of hydraulics. Since then some very significant improvements have been made in filters and seals, and with improvements in these areas a hydraulic servo system is certainly not second in reliability to a DC servomotor system. Oil leaks in hydraulic drives generally develop progressively. They are noticeable, they can often be repaired when convenient and they rarely cause unscheduled downtime. Nevertheless, they are annoying and can cause housekeeping problems. Danger of fire in some applications may require the use of phosphate ester or water-glycol types of fluid in place of conventional petroleum based hydraulic fluid.

In paint spraying and other applications the environment may present an explosion hazard and the robot must either be explosion proof or intrinsically safe so as not to ignite the combustible environment. Here the hydraulically driven robot has a great advantage over the electrical model since the electric energy from feedback devices and the energy to drive servo valves can be small enough not to ignite the explosive fuel-air mixture.

The last claimed advantage for hydraulics is that this power method lends itself to robot applications because energy can easily be stored in an accumulator and released when a burst of robot activity is called for. The 2000 series Unimate momentarily requires as much as 60 GPM which is supplied by a 17 GPM pump operating part time loading an accumulator. Because there are no convenient means to store electric energy, the designers of electrically driven robots tend to underpower the drives. To obtain the necessary dynamic performance they often use too high gear-ratios. The result is a snappy robot for small moves, but an embarassingly slow machine for large transfer moves.

In all of these discussions the question of size has so far been ignored. The cost of only some of the components is affected by size. The cost of a servo valve does not change much by size but the cost of an electric servo power amplifier will change greatly. The same goes for gears and other machined parts. A large, powerful robot normally works in more noisy and less pleasant surroundings than its smaller counterpart. A smaller robot will have an easier environment to contend with and probably a softer job. Also, because of its location, it will be treated better. All of these factors make it possible to design the small robot with a lesser safety factor than that required for a larger robot. As a result, the cost advantage of a hydraulically driven robot diminishes with size and when we talk about cost, we should consider total cost, including installation, maintenance and other operational expenses. All of that taken into consideration builds a very strong case for the electrical drive for the small robot.

The exact crossover point between hydraulic and electric drives may vary with robot configuration and the robot's intended use. Similar observations have been made by designers in other fields. Every drive has its pros and cons and will eventually find its proper place. In industrial handtools pneumatic motors are displacing electrical motors.

In some designs the proper choice was made at the start. We have electrically driven sewing machines and hydraulically operated backhoes, not the other way around.

Dynamic performance and accuracy

This discourse might very well have been entitled Dynamic Performance *versus* Accuracy, because these two qualities seem to be mutually exclusive. Closing out error of a servo to high accuracy is done at sacrifice of speed. While not as elegant a concept, it does appear to be as inexorable as the Heisenberg Uncertainty Principle, which, in particle physics, postulates that one cannot at the same time absolutely determine both the velocity and the position of a particle.

The analogy ought not to be overexercised. With diligent expenditure of money, ingenuity, and all the tools of modern servo theory, one can press the dynamic performance-accuracy impasse to levels well beyond that achieved by a simple proportional feedback servo.

A robot's speed can usually be evaluated in dollars (economic analysis in chapter 7 quantifies this for speeds 20% slower and 20% faster than a human operator). The marginal expenditure in gaining speed at no loss of accuracy is almost always cost effective.

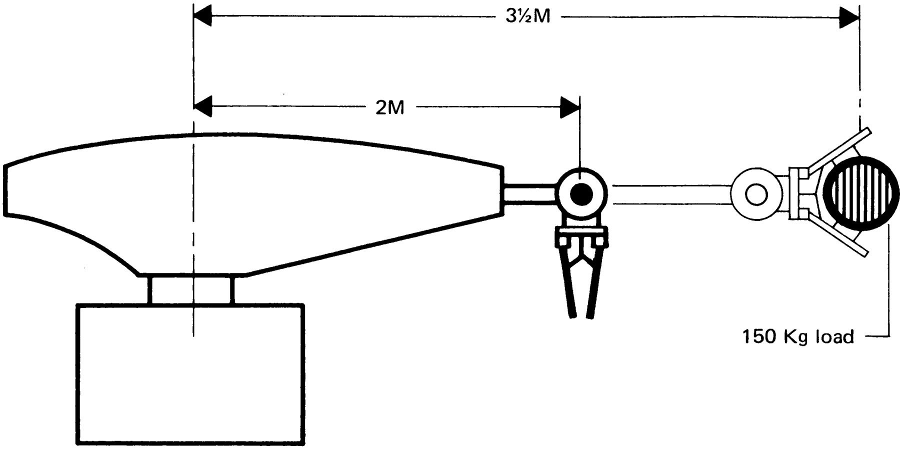


Figure 2.8 *Diagram of robot arm performance*
From fully retracted and unloaded to fully extended and carrying a 150 kg. load the moment of inertia changes from 70 KgMsec^2 to 230 KgMsec^2, a factor of over 3/1.

The problem can be quantified with reference to Figure 2.8. Consider a robot arm that has a retracted hand position of 2 meters and an extended hand position of 3½ meters. Consider also that this arm might carry a load of 150 kilograms, and that the arm should go from position-to-position, with or without load, at any extension and without overshoot. For the configuration of Figure 2.8, the variation in moment-of-inertia is from 70 KgMsec^2 when tucked in and unloaded to 230 KgMsec^2 when fully extended and loaded. To achieve a critically damped servo with position repeatability of 0.5 mm under all operating conditions is no mean chore. Note that 0.5 mm resolution for an arm with 300° of

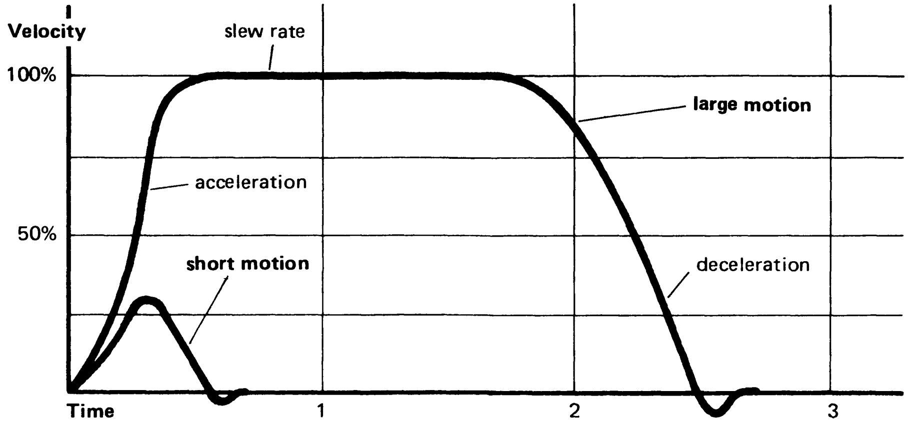


Figure 2.9 *Typical velocity traces for long and short arm motions*

rotation requires position encoding to an accuracy of 1 part in 33,000 or 2^{15}.

The foregoing deals only with a major robot arm articulation. In a full arm the interactions among the various articulations complicate both dynamic performance and accuracy. For example a robot arm designed to achieve an individual articulation natural frequency of 50 Hz, degenerates to an overall 17 Hz in a 6 articulation arm.

It is not the intention of this book to advise on robot design. Yet the manufacturing engineer should appreciate what a roboticist has to cope with in achieving requisite speed and accuracy. This may help protect him from 'specmanship'. The block diagram of Figure 2.10 functionally describes the key elements of a single articulation servo system with all of the 'bells and whistles' including velocity and acceleration feedback and inter-articulation bias signals.

To return to the issue of 'specmanship', it is common for robots to be offered with abbreviated specifications that list the slew rates of each articulation and the repeatability of each articulation. But, what is really needed is block point of time to go from position to position and net accuracy of all articulations in consort. Figure 2.9 shows two typical velocity traces for a short arm motion and for a large arm motion. It is evident that slew rate is no measure of elapsed time in making a motion, particularly a short motion in which slew rate may not be attained at all.

In estimating the time to complete a task (without actually simulating the entire process) the interface with the work place complicates the process. Paths to avoid obstacles add program steps. Some steps must be very precise, calling for closing out to zero error before the program advances. Other steps may be corners in a motion path which can be

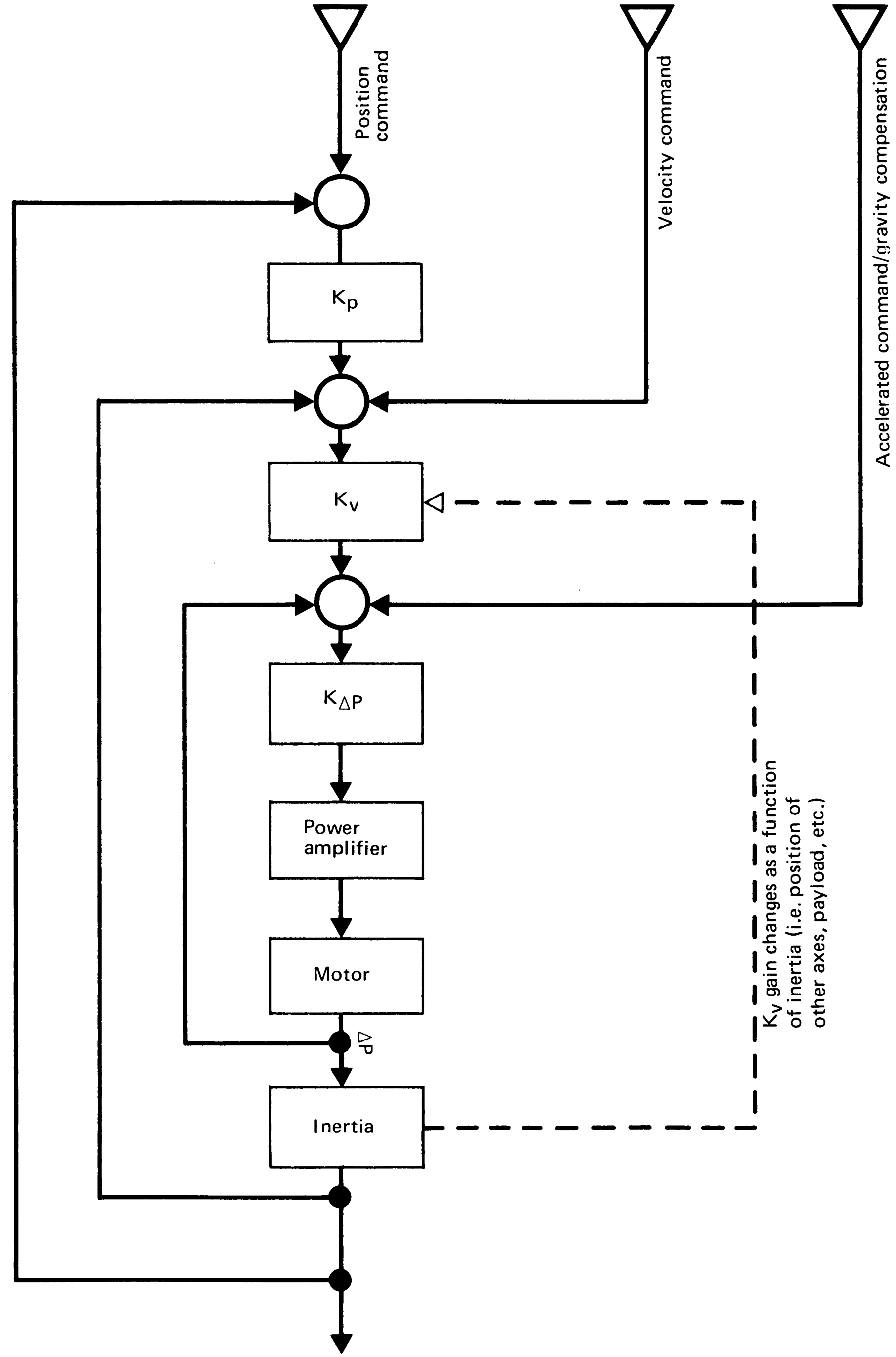


Figure 2.10 *Elements of a single articulation servo system*

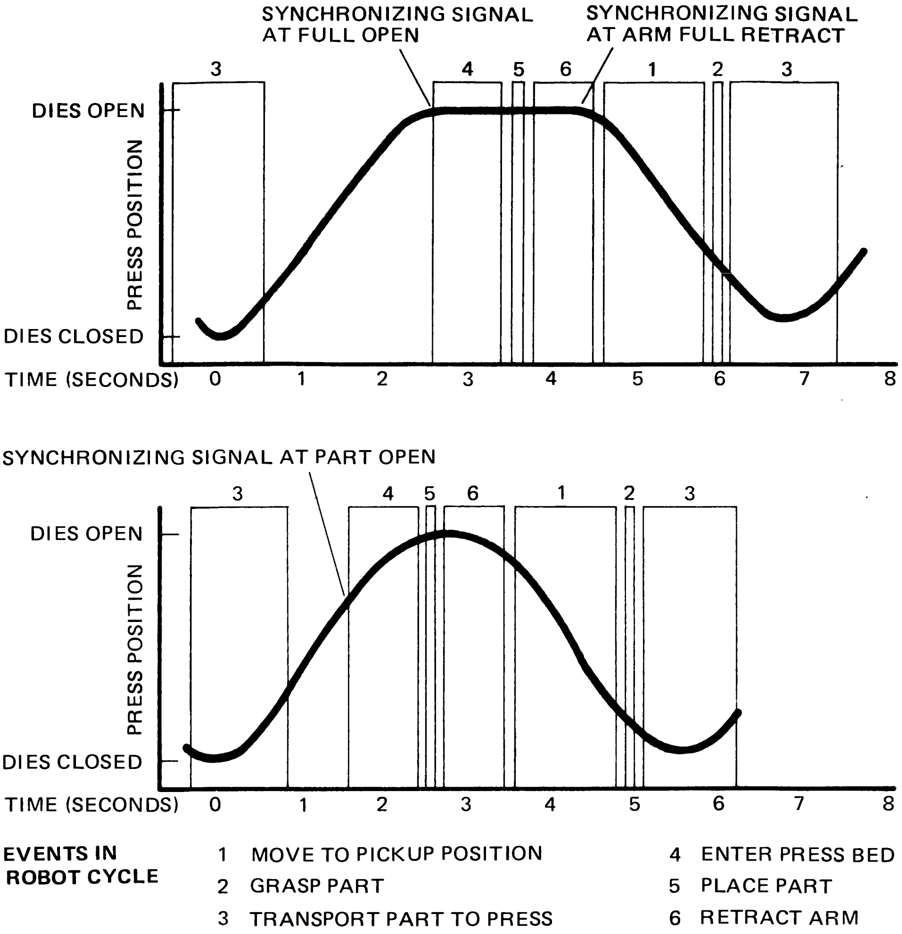


Figure 2.11 *The interlock system to reduce cycletime*

passed through on the fly. The use of interlock switches may introduce transport lags.

Simple programs often permit using a rule of thumb. For a 2000 series Unimate, if one allows 0.8 second for each motion taught, short steps as well as long, a time for program completion can be estimated quite closely. However, if a program is complex, as in spot welding a car body, there are too many variables to permit the use of such methods. In fact Unimation Inc. has developed an 18 page treatise to aid in forecasting program time for a multiplicity of robots spot welding an auto body. Factors considered are weld gun inertia, weld gun operating time, metal thickness, proximity of spots to one another, etc.

Sometimes program time is truly critical, such as when a robot is serving heavy, expensive capital equipment. If the production rate is paced by the robot rather than the capital equipment, the project is no longer viable because of loss in through-put.

Optimizing such a program may involve a range of tricks-of-the-trade. A typical application might be press-to-press transfer of automotive sheet-metal parts. A line of presses runs at a gross production rate of up to 700 parts per hour. At this rate a robot must make a complete transfer and return for the next pickup in 5.16 seconds. With presses on center-to-center distances of 6 meters, this is a demanding transfer speed. To meet this 700 per hour rate, a robot was modified by increasing the capacity of both hydraulic supply and servo valves. Acceleration and deceleration times were reduced at some sacrifice in damping and accuracy. This was compensated for by providing die nests with leads or strike bars. Finally, interlocks were refined so that the robot could make approaches and departures during the rise and fall of the presses' moving platens. Figure 2.11 shows how the time is shortened by tight interlocks that do not wait for press cycle completion. This strategy is not possible with human operators because of safety considerations.

Speed and accuracy! How is it that the human can do so well? The fully extended human arm has an unloaded natural frequency of only 3 Hz and the human's blind accuracy is much poorer than a robot's. What the human has is superb sensory aids. In motion the arm is guided by eyesight and proprioceptive muscle structure whose feedback mechanisms are not fully understood. Upon interactive contact, tactile data is added to the human's sensory richness. It may be that some measure of rudimentary vision and tactile sensing will ease the robot's servo demands when these qualities become commercially available. But, for the time being, the trade-off between dynamic performance and accuracy is a paramount design consideration. How a robot performs on this score is worthy of careful appraisal by the prospective user.

Chapter 3

End effectors: hands, grippers, pickups and tools

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

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

Methods of grasping

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

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

Some examples of appropriate methods are:

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

Mechanical grippers

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

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

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

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

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

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

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

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

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

This reduces to:

clamping force x 0.15 = 25 x 3
i.e. clamping force = 500 lbs

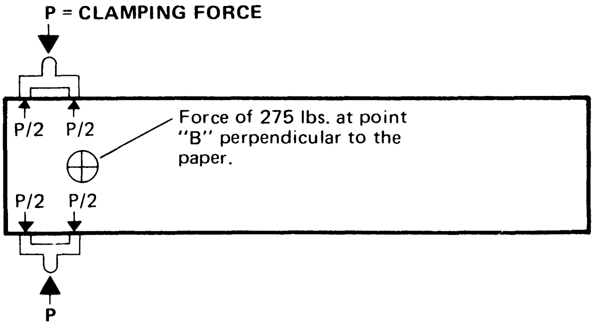
With a safety factor of two, the clamping force should therefore be 1000 pounds.

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

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

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

Figure 3.1 *Example showing calculation of grasping force*

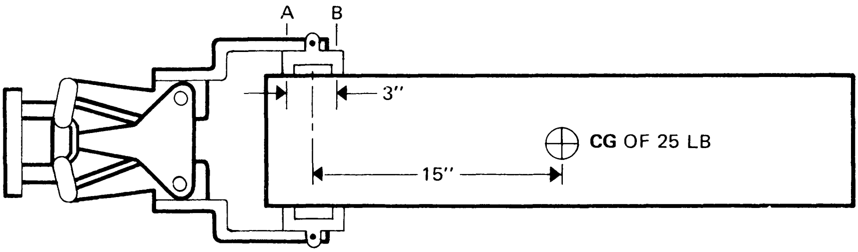


clamping force x friction coefficient (μ)
$\geq$ force at point "B"
$2 \ (P/2 \times \mu) = B$
$2 \ (P/2 \times 0.15) = 275$
$P = 1830$ lbs

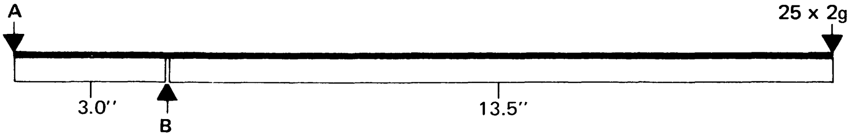
with a safety factor of 2, the required clamping force is 3660 lbs.

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

The situation may be represented thus:



This simplifies into the following force diagram:

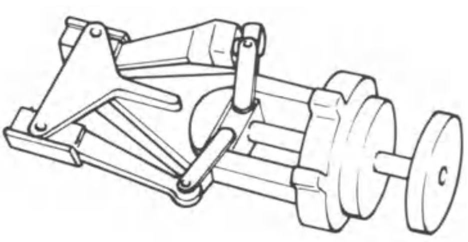


force at point "A" =
$$\frac{25 \times 2}{3} \times 13.5 = 225 \text{ lbs}$$

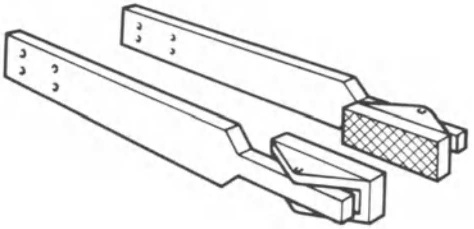
force at point "B" =
$225 + (25 \times 2) = 275$ lbs

Figure 3.1 (continued)

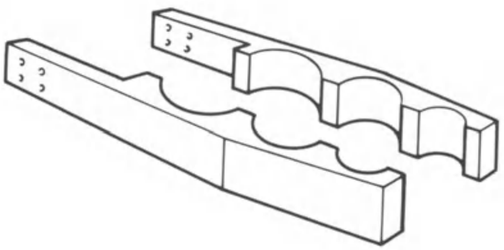
Some indication of the very wide variety of mechanical grippers which have been designed to meet different robot applications can be gained from Figure 3.2. The selection is by no means representative of all that is available or possible. As previously mentioned, grippers are the one area of robotization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



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

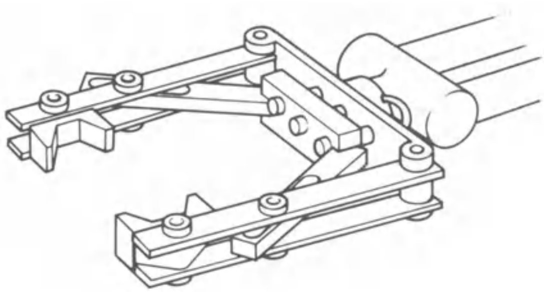


Fingers self-aligning
Self-aligning pads for fingers are valuable for assuring a secure grip on a flat-sided part. 'Cocking' of the part is highly unlikely when these pads are employed.

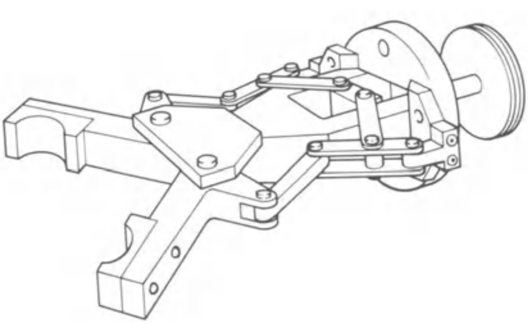


Fingers for grasping different size parts
A particular finger design need not be restricted to parts within a limited range of sizes. Perhaps the fingers can be equipped with extended pads having several cavities for parts of differing sizes and shapes, or for parts that change shape during processing.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

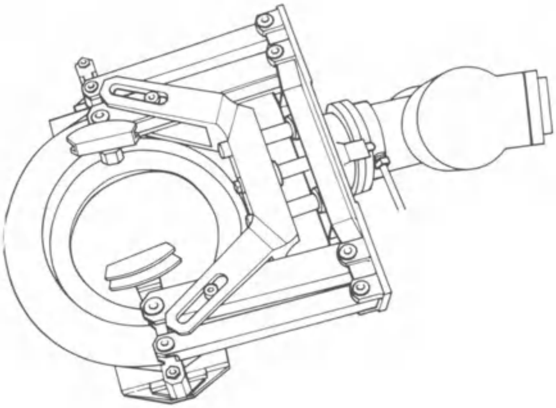
Figure 3.2 *Examples of mechanical grippers*



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

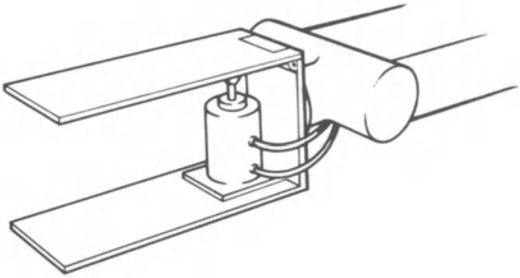


Wide-opening hand
When the part to be picked up is not always to be found in a constant orientation or at the same site, a wide-opening hand may be recommended. As it closes, this hand will sweep the inexactly located part into its grasp.
If the part to be grasped is always precisely positioned for pick-up,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

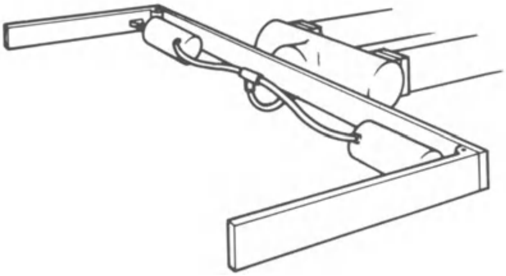


Cam-operated hand with inside and outside jaws
Assume that a part is re-oriented between the time when the part is placed in a machine and when it is removed. This special hand is one of those which will deal with this problem. When the part is oriented as shown, the hand can grasp it on the OD by employing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

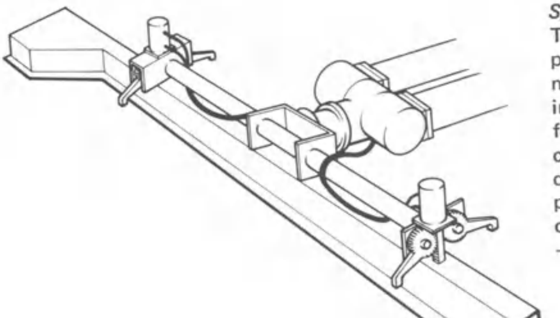
Figure 3.2 (continued)



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

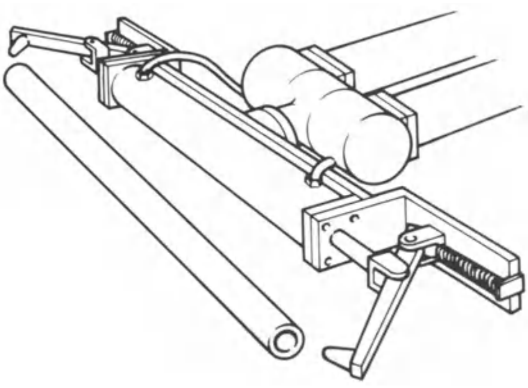


Special hand for cartons
The dual-jaw hand will open wide to grasp inexactly located objects of light weight. Lifting and placement of cardboard cartons is an application. Actuators and jaws can be re-mounted in any of several positions on the fixed back plate, making it practical for the same dual-jaw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

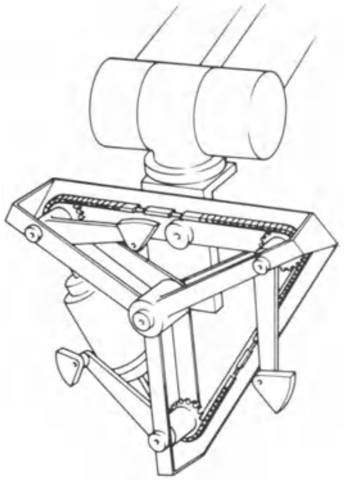


Special hand with modular gripper
This special hand, with pair of pneumatic actuators, is one of the many special hand designs for industrial robots. It would be suitable for parts of light weight. Lifting capacity is dependent upon friction developed by the fingers, but heavier parts could be handled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

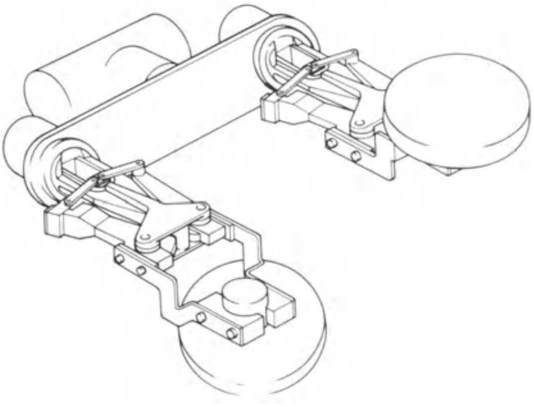
Figure 3.2 (continued)



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



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



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

Figure 3.2 (continued)

Vacuum systems

Vacuum cups

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

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

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

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

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

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

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

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

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

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

Vacuum pump versus *venturi*

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

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

Disadvantages:

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

The advantages of a venturi:

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

Disadvantages:

- ○ Very noisy
- ○ High cost of operation

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

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

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

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

Special considerations

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

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

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

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

Magnetic pickups

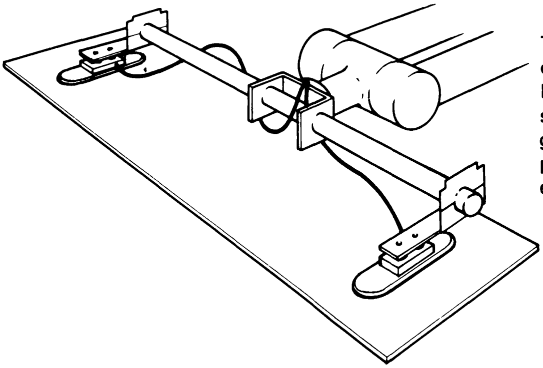
Parts handling for various processing operations can be accomplished in several ways but if the parts are of ferrous content, magnetic handling should be one of the methods to receive consideration.

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

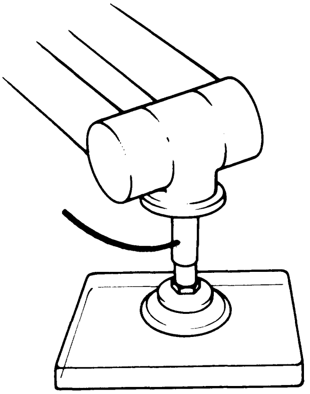
Magnets fall into two principal categories, namely permanent and electro. Either of these types can be adapted within reasonable limits to handle parts having various shapes and often it is possible to handle several different shapes with the same magnet.

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

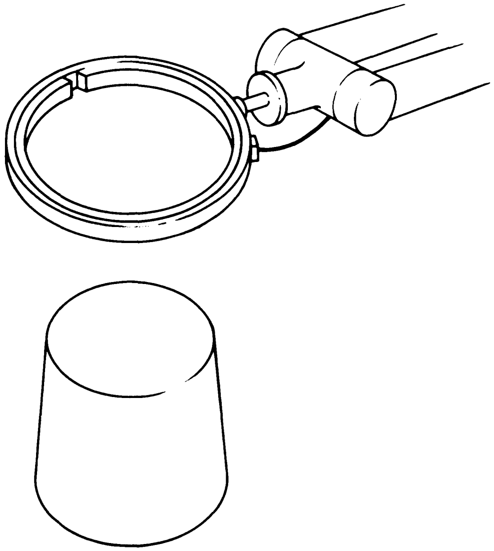
Permanent magnets do not require a power source for operation which makes them well adapted for hazardous atmospheres that require explosion proof electrical equipment. They do, however, require a means of separating material from the magnet. To accomplish this, a stripper device may be employed or if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



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



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



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

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

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

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

1 SHAPE OF PART

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

2 WEIGHT

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

3 TEMPERATURE

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

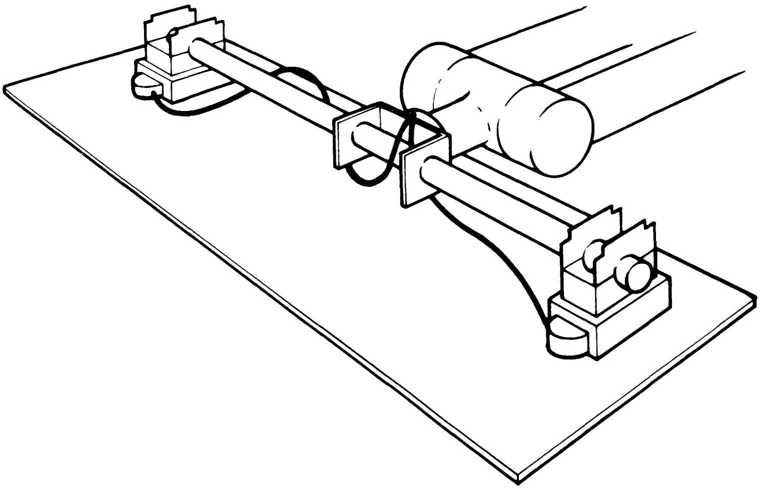
In all cases, frequency and length of contact with the hot part and the length determine most of the operating limits.

4 SURFACE CONDITION

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

5 POSITION TO BE HANDLED

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



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

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

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

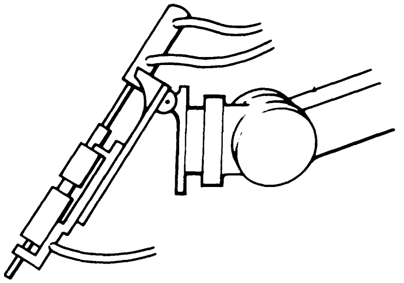
A typical electromagnetic pickup designed for use with flat surfaces is illustrated in Figure 3.4.

Tools

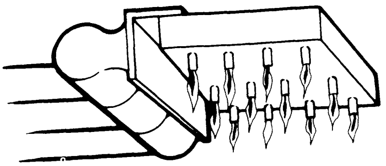
With various grasping and pickup devices, robots clumsily imitate what a human operator might do. Sometimes the human is directed to pick up a tool and use it continuously. When a robot takes over such a task the tool might just as well be fastened to the robot's extremity permanently. Or, if the robot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

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

A range of such tools is illustrated in Figure 3.5.

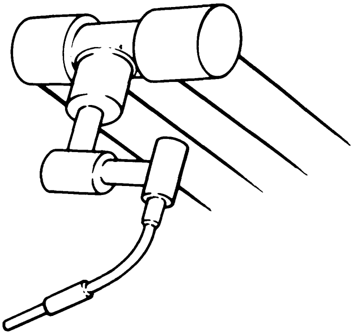


Stud-welding head
Equipping an industrial robot with a stud-welding head is also practical. Studs are fed to the head from a tubular feeder suspended from overhead.

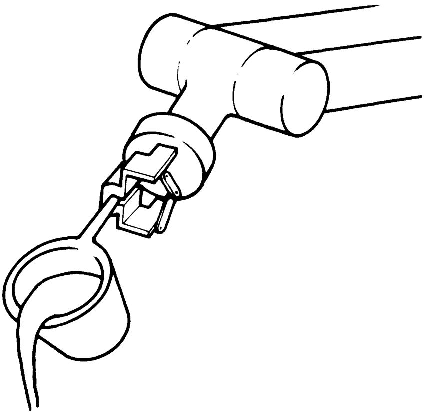


Heating torch
The industrial robot can also manipulate a heating torch to bake out foundry molds by playing the torch over the surface, letting the flame linger where more heat input is needed. Fuel is saved because heat is applied directly, and the bakeout is faster than it would be if the molds were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

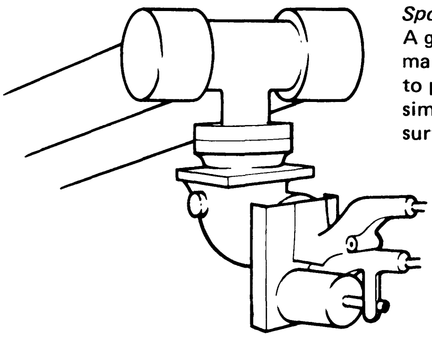
Figure 3.5 *Examples of tools fastened to robot wrists*



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

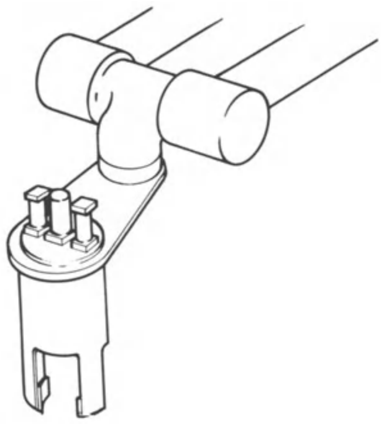


Ladle
Ladling hot materials such as molten metal is a hot and hazardous job for which industrial robots are well-suited. In piston casting, permanent mold die casting, and related applications, the robot can be programmed to scoop up and transfer the molten metal from the pot to the mold, and then do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

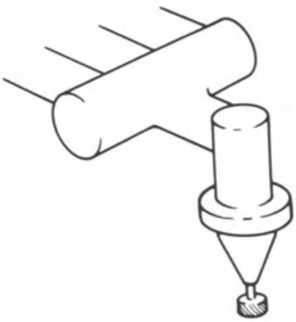


Spotwelding gun
A general purpose industrial robot can maneuver and operate a spotwelding gun to place a series of spot welds on flat, simple-curved, or compound-curved surfaces.

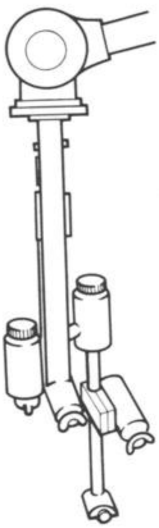
Figure 3.5 (continued)



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

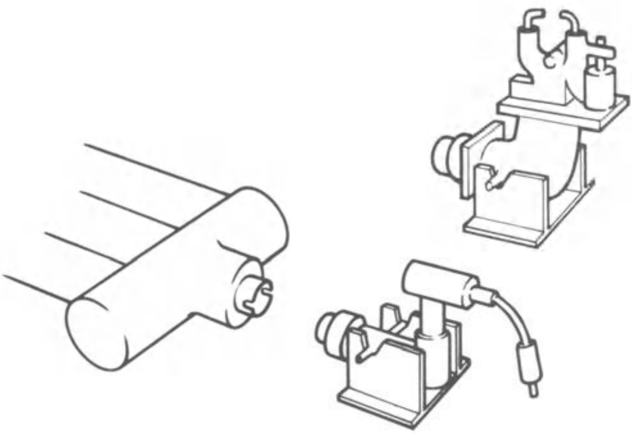


Routers, sanders and grinders
A routing head, grinder, belt sander, or disc sander can be mounted readily on the wrist of an industrial robot. Thus equipped, the robot can rout workpiece edges, remove flash from plastic parts, and do rough snagging of castings.



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

Figure 3.5 (continued)



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

Figure 3.5 (continued)

Chapter 4

Matching robots to the workplace

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

Part orientation

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

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

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

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

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

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

Interlocks and sequence control

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

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

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

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

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

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

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

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

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

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

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

Outline example of a sequence control problem

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

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

Other requirements of this application are:

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

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

Detailed analysis of setting up a sequence control system

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

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

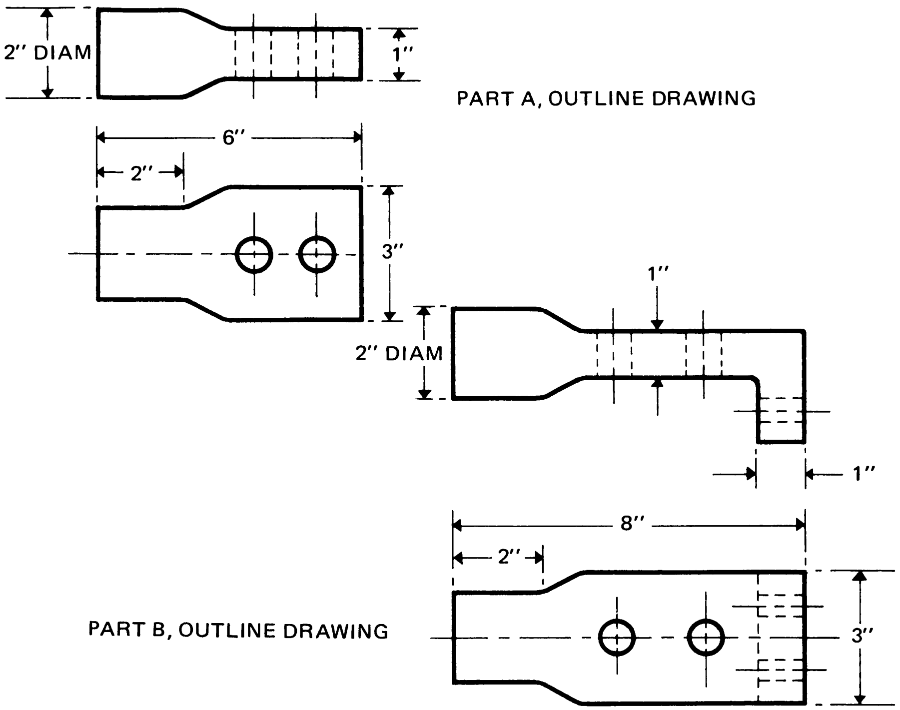

Figure 4.1 *Sequence control example: the workpieces*

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

MATERIALS HANDLING SEQUENCE

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

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

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

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

ANALYSIS OF THE MACHINING CYCLE

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

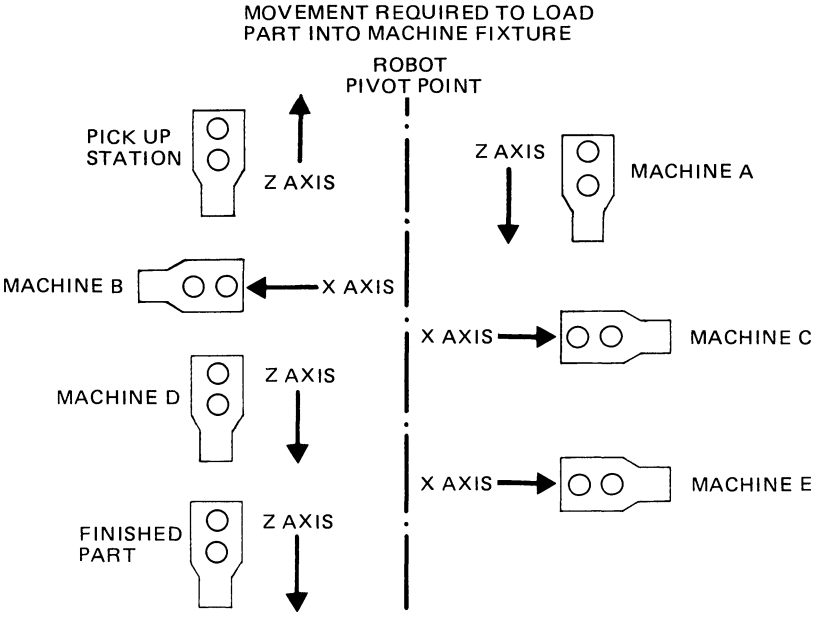

Figure 4.2 *Sequence control example: workpiece feed positions*

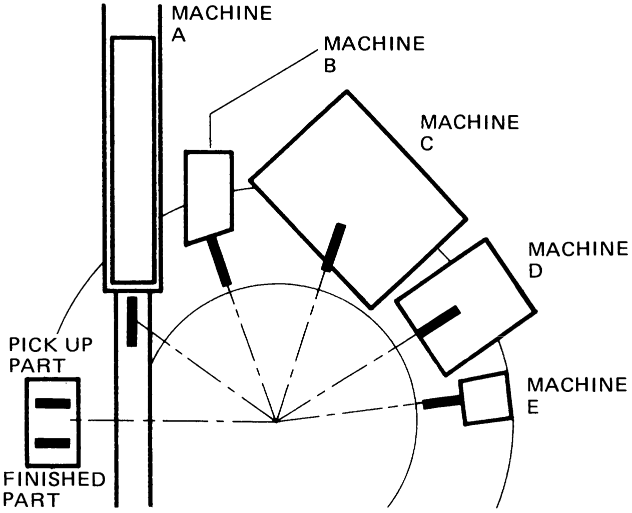

Figure 4.3 *Sequence control example: equipment layout*

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

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

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

INTERLOCKS ANALYSIS

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

Pickup station
Signal to robot that a part is present.

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

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

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

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

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

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

GRIPPING REQUIREMENTS

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

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

Workplace layout

Work configurations can be classified in the following four ways:

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

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

Arranging work around the robot

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

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

Work travels past the robot

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

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

MOVING-BASE LINE TRACKING

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

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

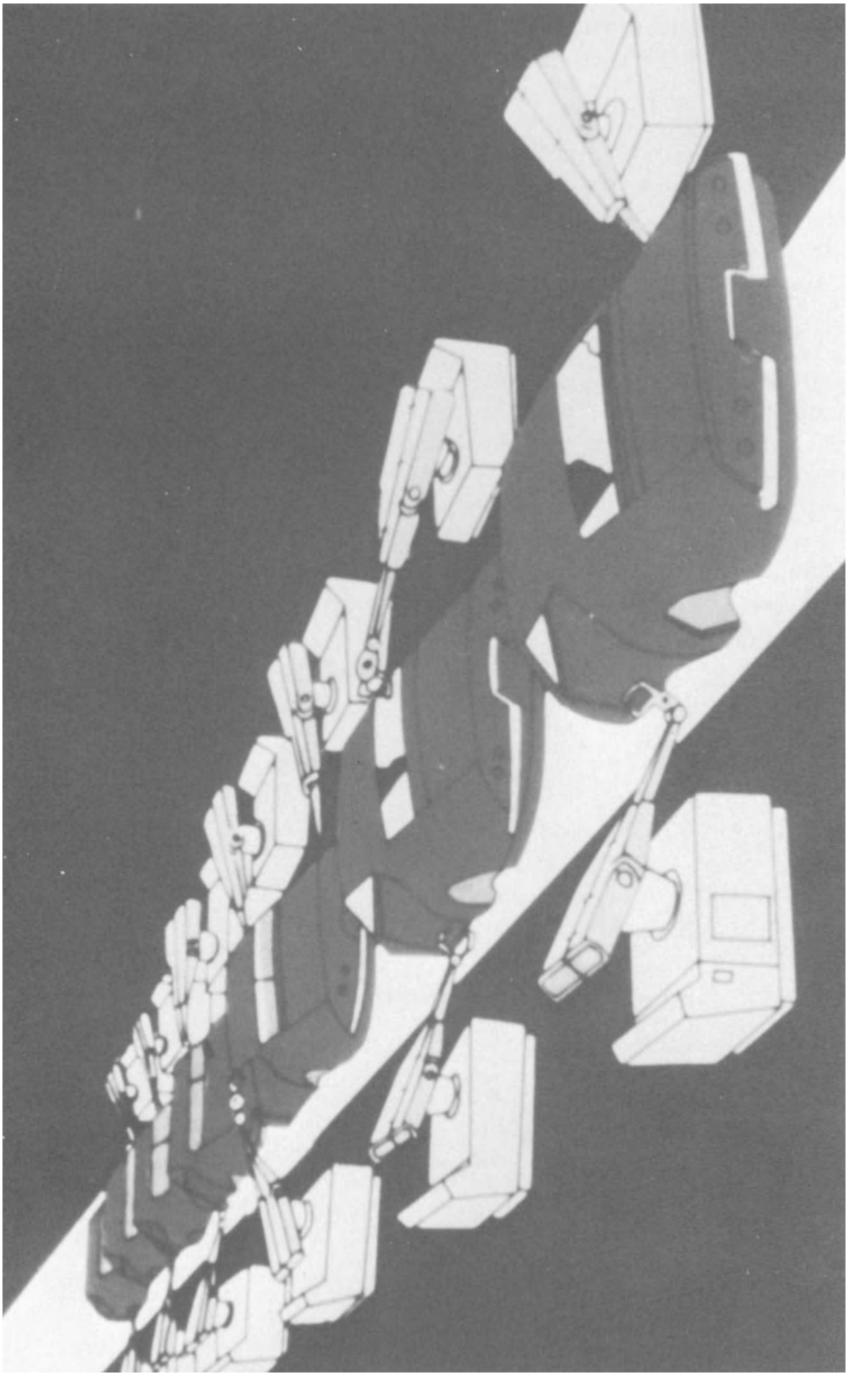

Figure 4.4 *Work comes to robot*

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

2. STATIONARY-BASE LINE TRACKING

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

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

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

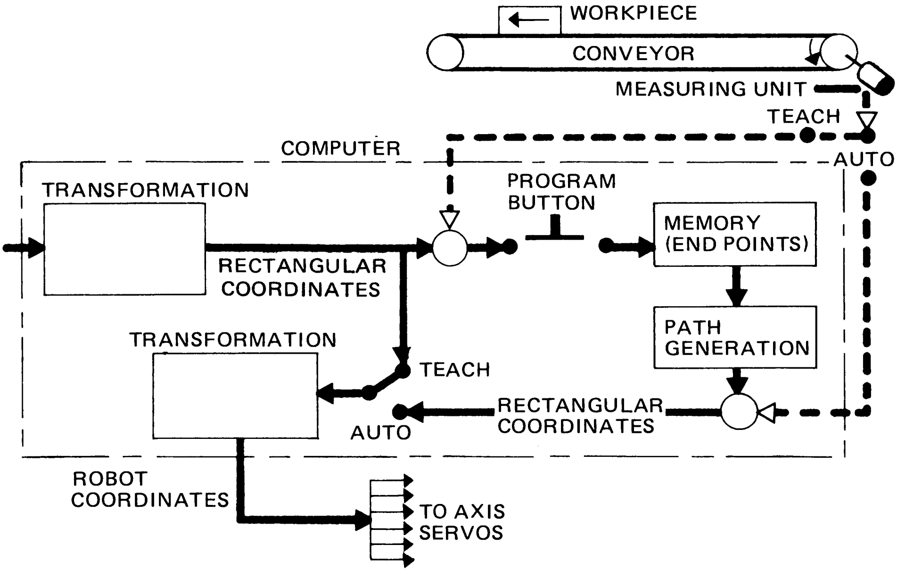

Figure 4.5 *Work travels past robot – diagram of tracking and control system*

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

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

IMPLEMENTATION OF STATIONARY-BASE LINE TRACKING

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

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

CONSIDERATIONS FOR STATIONARY-BASED TRACKING APPLICATIONS

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

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

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

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

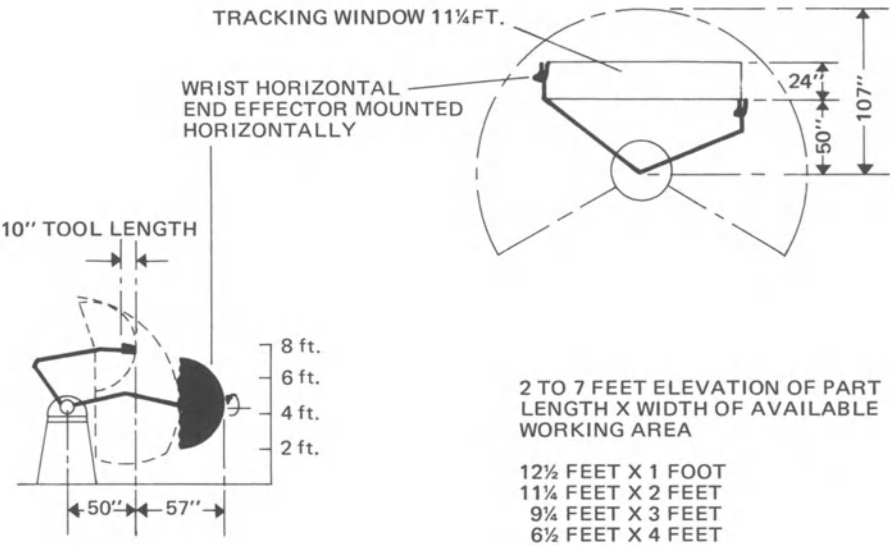

Figure 4.6 *Work travels past robot – examples of tracking windows*

Robot travels to work

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

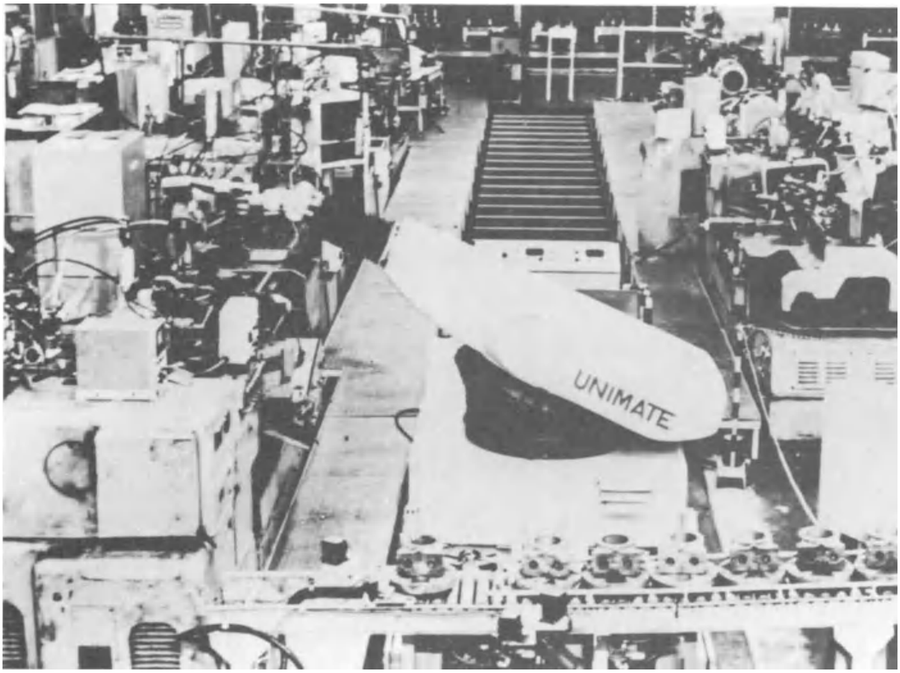

Figure 4.7 *Robot travels to work – track mounted robot serving 11 machine tools*

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

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

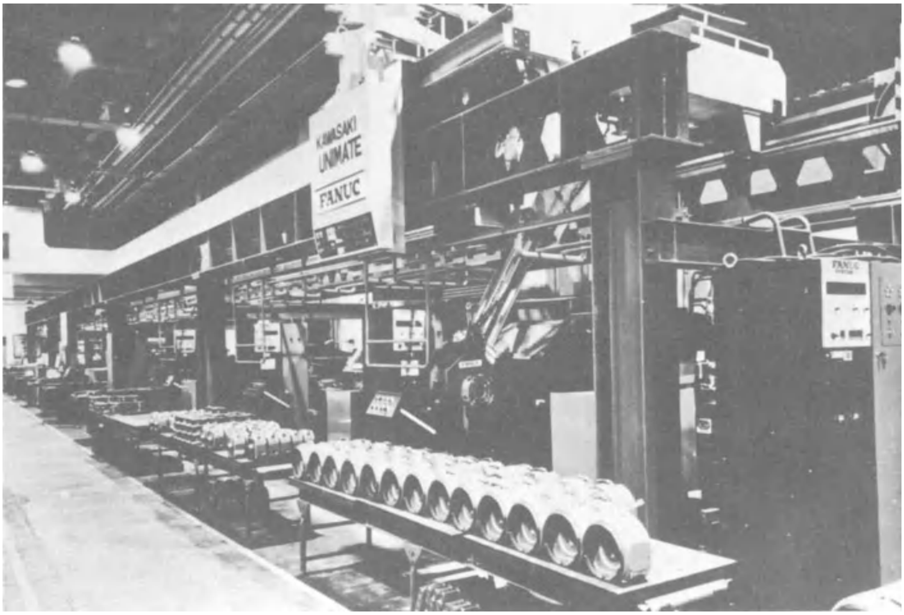

Figure 4.8 *Robot travels to work – overhead robot serving eight NC lathes*

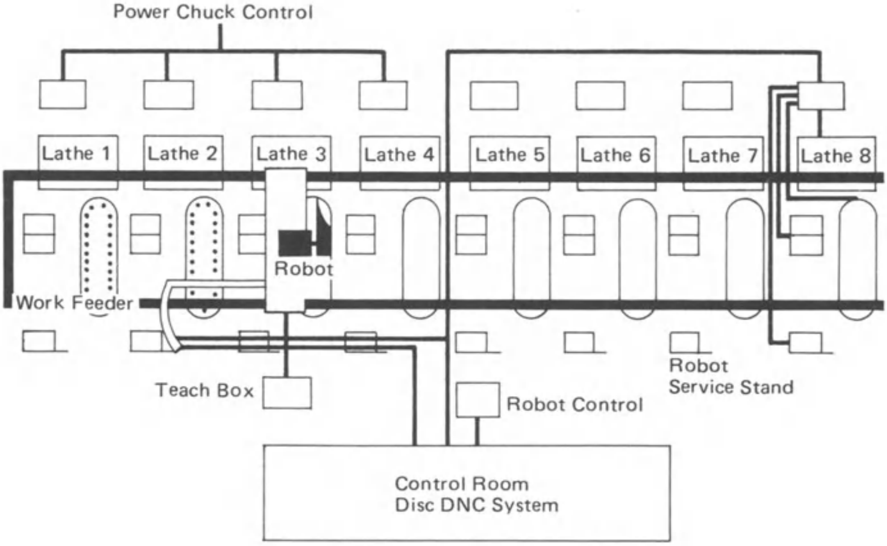

Figure 4.9 *Robot travels to work – diagram of overhead robot system portrayed in Figure 4.8*

Chapter 5

Reliability, maintenance and safety

Experience over millions of robot operating hours in manufacturing industry has proved that robots can be both reliable and safe. Their reliability has been proven by demonstrating the ability to work for hour after hour, day after day, in hostile conditions. They do this with only the rare breakdown. When they do break down, as often as not their downtime is short, because diagnostic routines enable the maintenance workers to get them back on stream without delay. On a parallel with their reliability performance, robots have been proved safe: accidents involving injury to human beings are exceedingly unusual. Serious injury has never occurred. These impressive performance records in reliability and safety have been brought about by attention to design and by commonsense application of robots in use.

Environmental factors in robot systems

When equipment is designed for a specific purpose, such as a military application, it is usually possible to specify a set of environmental conditions surrounding the operation of that equipment. These conditions then form part of the design specification, and they play a large part in the choice of individual components, and in the layout and construction of the final hardware. Such is not the case for industrial robots. There is no single set of environmental conditions which covers all possible industrial possibilities. Nevertheless, after many millions of hours of industrial robot experience, it has been possible to come up with a design and quality test procedure that seems to have conquered the hazards presented by most known industrial environments. Test and design methods are, to some extent, empirical, and so will continue to evolve as more and more experience is gained.

Figure 5.1 lists the primary environmental factors that have to be considered in robot design. Because these conditions are described qualitatively, there may be merit in expanding upon this tabulation with even more qualitative discussion to give the would-be robot designer a ‘gut feeling’ for the job at hand.

1 Ambient temperature: up to 120°F without cooling air
2 Radiant heating: source temperature up to 2000°F
3 Shock: excursions up to ½ inch, repetitions to 2/second
4 Electrical noise: line drop-outs, motor starting transients; RF heating
5 Liquid sprays: water and other coolants, often corrosive
6 Fumes & vapors: process chemicals, steam cleaning
7 Particulate matter: sand, metallic dust, hot slag
8 Fire & explosion risk: open flame, explosive gas & vapor mixtures

Figure 5.1 *Hazards in the industrial environment*

HEAT

Ordinarily, a human worker is not required to function continuously in an ambient temperature over 120° F and therefore this is a reasonable maximum standard for an industrial robot. Both the human operator and the industrial robot are afforded cooling air if the workplace temperature exceeds 120° F. In some instances particular attention must be paid to radiant heating where the worker is the target of open furnaces, lehrs and hot parts in process. Radiation shields are sometimes used and a robot may expect to be provided with a curtain quench for its extremities.

SHOCK AND VIBRATION

There are not too many instances when an individual robot must endure severe vibration conditions. It is usually lugged to massive floor members and vibration from associated equipment is minimal. On the other hand, shock can be severe. Some hammer forge operations develop shock so severe that it can be felt in offices 300 yards away.

ELECTRICAL NOISE AND INTERFERENCE

One of the most frustrating environmental conditions to plague a robot designer is electrical noise. Designers have been unable to create a noise standard which would enable us to extrapolate in-house testing to noise immunity in the field. Any new design is put into the field in operations which we have found to be particularly 'dirty' as regards electrical noise.

An electrical line dropout that might cause a computation error in a computer, means only a burst of 'garbage' data output. For an industrial robot it might mean physical action damaging to the robot or to the equipment with which it is associated. Noise insensitivity is crucial and without a clear definition of the noise environment, design becomes an iterative process cycling back and forth between the field and the laboratory.

LIQUID SPRAYS, GASES AND HARMFUL PARTICLES

There are lots of things that land on or diffuse through industrial robots in factories. These are often the same things that are designated as health hazards to human operators. The 'black lung' human debility has its counterpart in the susceptibly designed industrial robot. Some examples will help make the point:

- In investment casting, the atmosphere is heavily contaminated with alcohol-ammonia fumes which are highly injurious to any open switch contact. The same operation also includes particulate contamination and gear trains and sliding bearings require absolute protection.
- In one foundry application carbonized-silica particles are continuously in the atmosphere and fall to the floor at the rate of ¼ inch per day. The material is extremely abrasive, and with any moisture at all, corrosive to electronics.
- Heat treatment processes often involve combination of high temperature and high humidity. This may be compounded by the salt solution which is used in heat treatment and which can build up on the industrial robot.
- In some forging operations, die lubricant is applied copiously and the process impels the lubricant onto all surrounding equipment. This water-suspended graphite-based material builds up on the equipment and steam cleaning may be necessary daily. Steam cleaning itself is one of an industrial robot's environmental hazards.
- Sparks fly continuously in resistance welding set ups and flying metal particles will bond to open metal surfaces.
- A robot does not stand aside when molten metal is shot into a casting machine and therefore it may be exposed to slag spurting out between die parting lines. The slag is hot, it must be endured and the robot must occasionally suffer hammer and chisel removal of the build up.

RISK OF FIRE OR EXPLOSION

A man is inherently non-flammable and when admonished not to smoke he is non-igniting. When a robot stands in at a job where there is a continuing open flame, there must be protection against leakage of flammable servo oil that might cause a serious fire. In a job where an explosive atmosphere is created by the volatile carriers of paint, for instance, the robot must not have any design element capable of creating a spark.

Examples of hazardous situations

The following cases illustrate robots being subjected to some of the risks generated in typical industrial applications.

- In Figure 5.2, a robot services a die casting machine, suffering the perils of its stance at the die parting line. Note the protective

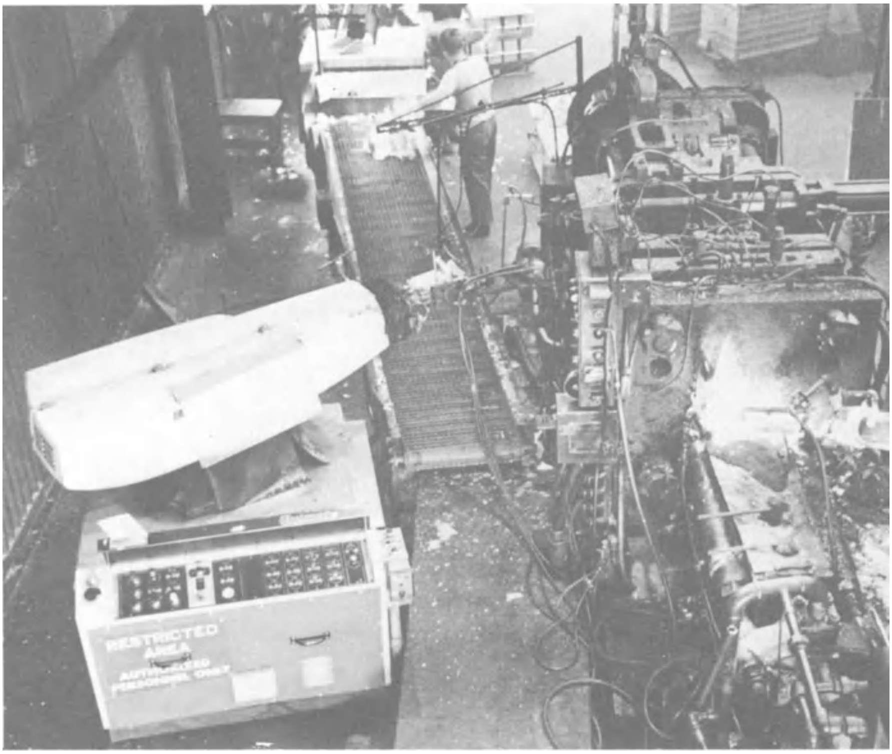

Figure 5.2 *Hazardous situation: robot services die casting machine*

baffle on its boom cover and the skirt below.

- Figure 5.3 shows a robot transferring billets in and out of a rotary furnace for heating just prior to a forging operation.
- In high energy forging, the billet is formed in one pass. Figure 5.4 shows the robot re-entering the press bed to extract the formed part.
- The chips created in machining are a hazard to robots. A boot around extension rods plus tight seals on wrist gearing are essential to long life in the application shown in Figure 5.5.
- Figure 5.6 shows the robot on a spot welding line. The robot must endure sparks, oil leaks and cooling water spray.

Designing robots for industrial environments

In designing industrial robots the primary influence is the nature of the jobs to be done. Once manipulative power, sphere of influence, speed, strength and memory capacity have been established, environmental conditions can be brought to bear upon the design.

Some examples of design concessions to the environment follow:

- Considering some of the hot and hostile places that a robot's hand must enter, it is desirable to eliminate all electrics and servos from robot extremities.
- In many applications it is entirely proper to package the robot as a self-contained entity, but there is an advantage to a design in which the electronics may be mounted separately. In extreme

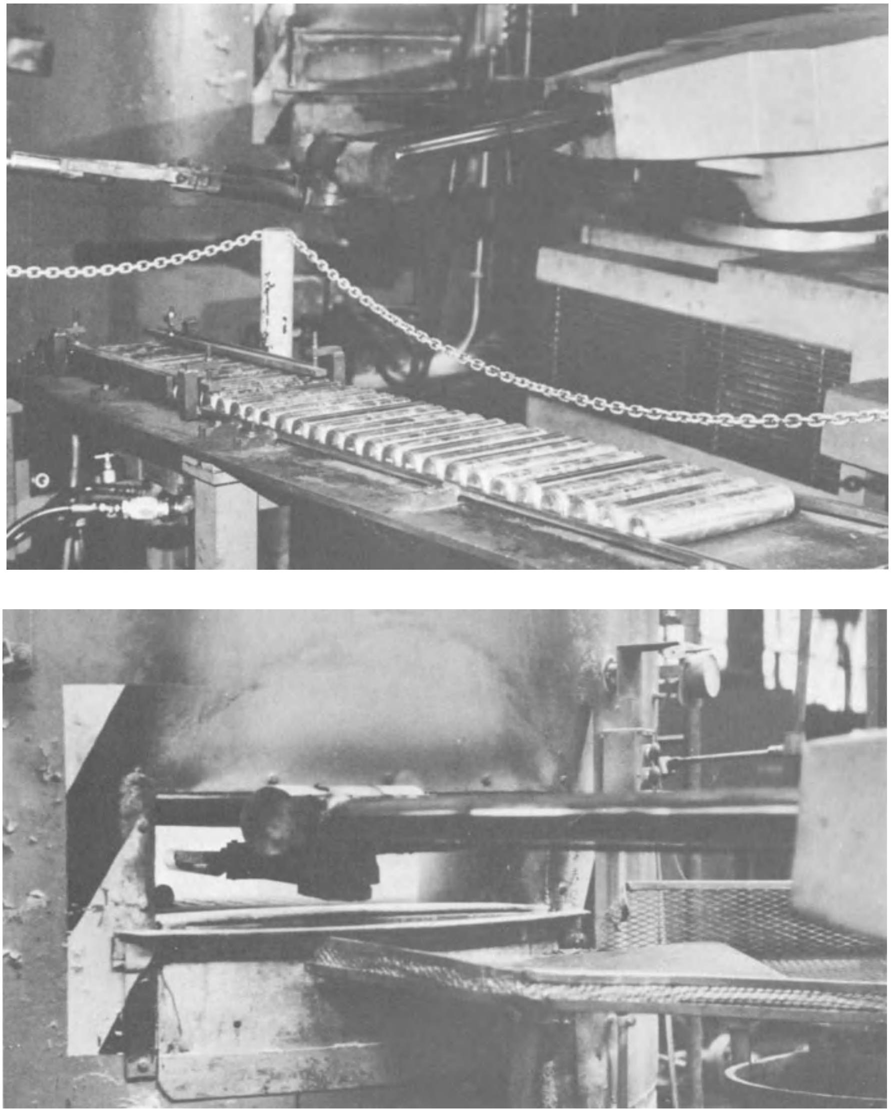

Figure 5.3 *Hazardous situation: robot transferring billets in and out of rotary furnace*

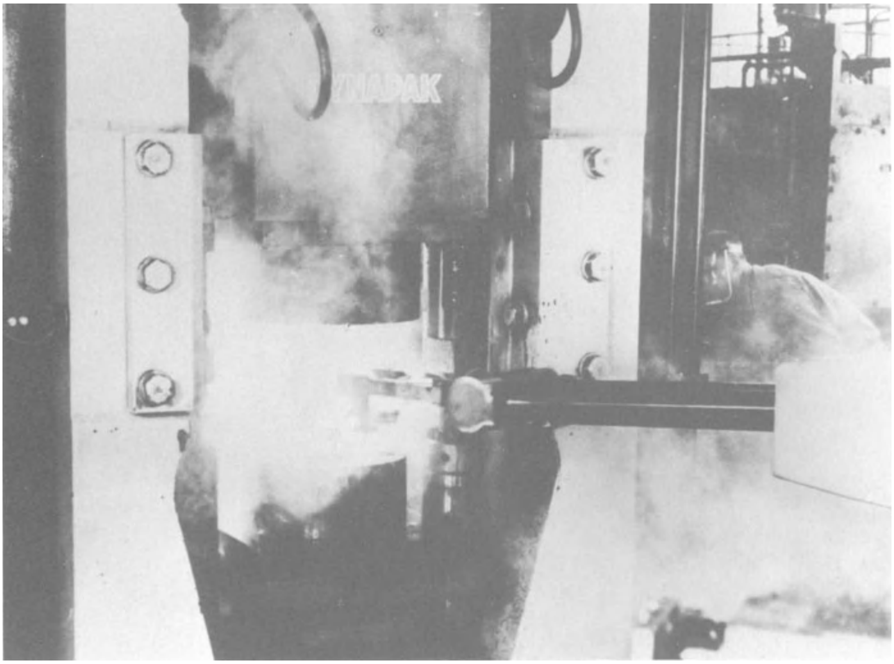

Figure 5.4 *Hazardous situation: robot re-entering press bed*

shock conditions it is convenient to be able to mount the control console on a shock absorbing pad and the remote location may be necessary to ensure life in a corrosive atmosphere. Going further, if the power supply of the robot can also be separated from the robot's arm then the arm may be introduced all alone into explosive atmospheres such as paint rooms.

○ With hot metal often flying about, it is important that all of the robot's skin be of non-flammable construction.

○ Where robot articulations are exposed in rotating or sliding joints, the joints should be booted to protect against abrasive dust collection.

○ A part answer to fire hazard conditions is provided by non-flammable fluids for lubrication and hydraulics. Such are available as an option because there is a significant cost disadvantage to their introduction.

○ If air is particularly dirty, air cooling may not be practical and the option to use water cooling should be made available. In any event, all cooling air should first go through filtration and enter enclosures to provide positive internal pressure.

○ Dust and dirt seem to be able to infiltrate the tightest crevices and therefore drive trains should use hardened gears and be pressurized to exclude contamination.

- Robot logic design should be heavily protected from power line spikes and noise pickup entering through any of the robot's communication links with surrounding equipment.

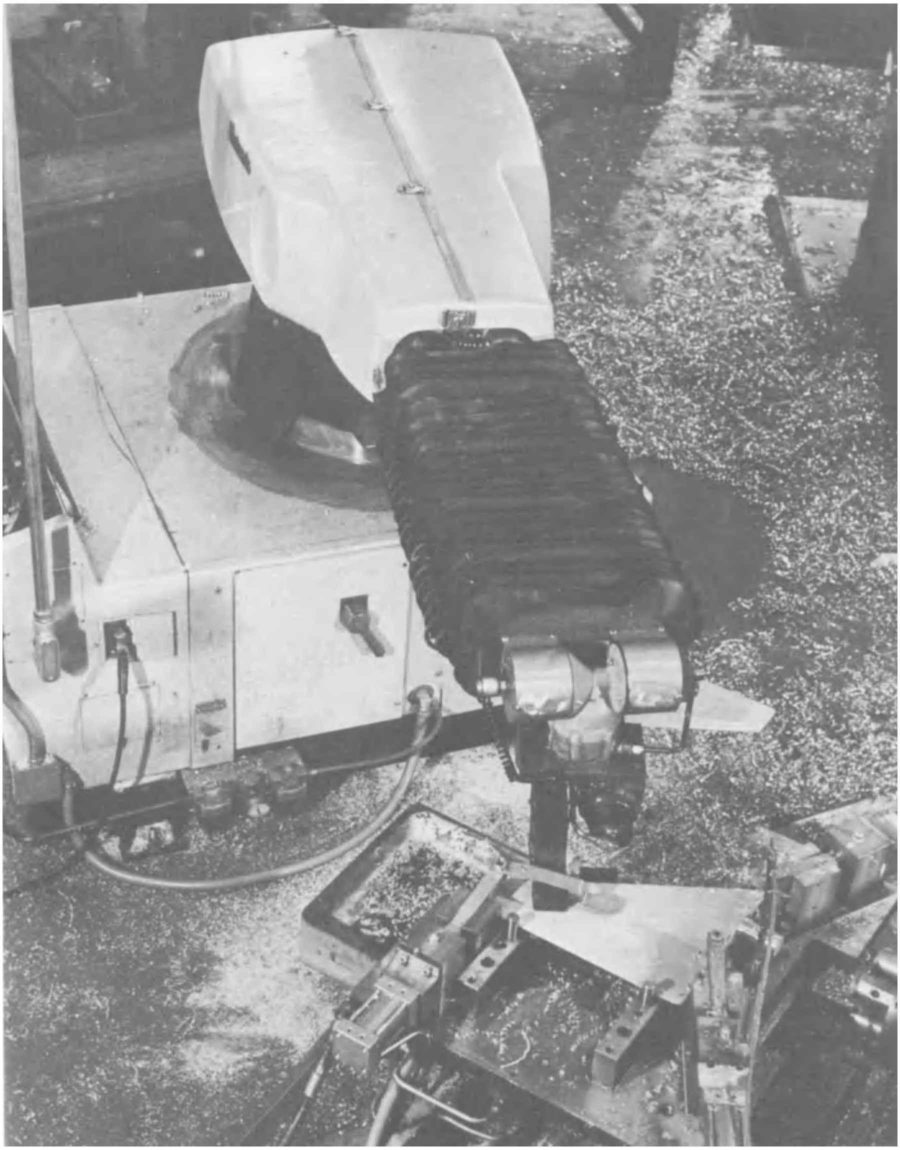

Figure 5.5 *Hazardous situation: robot protected from machining chips*

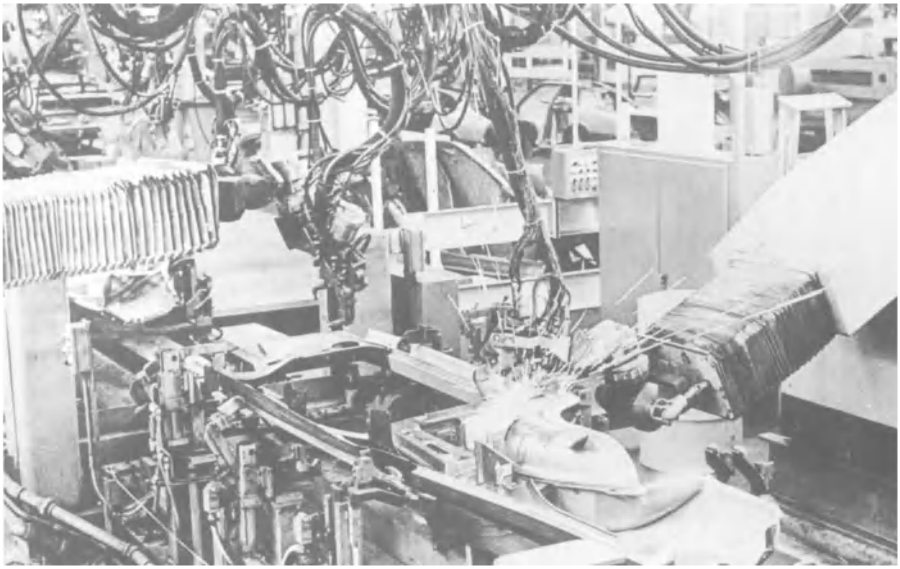

Figure 5.6 *Hazardous situation: robot subjected to sparks, oil leaks and water spray on spot welding line*

Reliability targets

There are two concepts to be considered in a discussion of reliability: one is Mean Time Between Failure (MTBF), and the other is 'downtime'. Clearly, there is a relationship between the time interval between failures and the total amount of downtime; but the correlation is not linear because there is the additional variable of Mean Time To Repair (MTTR). Thus, an otherwise satisfactory MTBF could result in unacceptable downtime if the time to repair is excessive.

An industrial robot is usually working in conjunction with another piece of productive machinery. When the industrial robot is down, and there is no provision for manual backup, the production machinery is also down. Industrial experience indicates that for most applications, uptime must exceed 97% to satisfy the users of industrial robots. This rule of thumb is somewhat dependent upon the specific application. In an operation such as die casting, which inherently includes a lot of downtime, the process is not as sensitive to robot downtime. In a glass manufacturing plant, which is very akin to a continuous process, there may be need for uptime of 99.5% and if this is not attainable, provision must be made for backup labor which might be supplied by a backup relief human crew or by spare robots.

If the design goal is a downtime of no more than 2%, and if we then conjecture that the robot manufacturer can always offer next-day service, and that all robots are working on a two-shift basis, the most likely downtime per incident becomes 8 hours. If the downtime per incident is 8 hours then a 400-hour Mean Time Between Failure must be the standard to hold overall downtime under 2%.

Theoretical reliability assessment

Given a rough target to aim at for downtime, it is interesting to consider how the theoretical reliability performance of a robot is evaluated. In the case of the Unimate robot, which has a long design history, the design standard was arrived at against a reliability study covering all the system components. This study was exhaustive, and the theoretical contribution of every component towards a total system failure rate was taken into account. This work was undertaken by an independent organization, Bird Engineering Research Associates, Inc., which specializes in reliability assessment. The Bird Report to Unimation Inc. concluded that Unimation's system design justified achieving an MTBF of 500 hours without incurring prohibitive costs in component design, system design, manufacturing, and quality control procedures.

The complete analysis was, of course, voluminous, but an appreciation of the method can be gleaned from an overview. To predict the failure rates for all of the components in the Unimate, Bird relied upon notebooks which were prepared under U.S. Government contract to aid prediction of reliability of space vehicle systems. For electronic components, the Rome Air Development Center Notebook, TR-67-108, was used and for mechanical hydraulic components Bird used the U.S. Navy's Failure Rate Data (FARADA) Notebook. Both of these references were cross-correlated with other similar data banks.

Figure 5.7 is a tabulation of reliability feasibility for electronic/electrical elements. It will be noted in this table that the expected MTBF for parts only is 1800 hours. Because of the contribution of other (non-parts) the estimated MTBF drops to 1217 hours. The non-part failure rate is a system failure rate due to tolerance buildup, critical interface tolerances, customer abuse, unforeseen environmental problems, etc. This type of failure occurs in analog systems at a rate proportional to the complexity of the system and for the Unimate this was established by the consultants by comparing complexity to similar systems for which massive data exists. Evidently, the upper limit for an MTBF would be the 1800 hours due to parts only. This upper limit could be approached only at high dollar cost and therefore if the more modest 1217 hour goal were not sufficient, it would be necessary to examine other alternatives including going back to the original design concept.

Figure 5.8 is a table which integrates the electronic/electrical and mechanical/hydraulic failure rates to predict an overall attainable

Component or Element	**Part Failure Rates (x10^{-6})**
Common Group	
Power Supply	54
Shift Registers	103
Memory	112
Relay Tree	125
Control Panel	11
Memory Sequence Control	16
Home Options (3 x 60)	11
Scanner	3
Comparator	14
Sequence Control	7
Operate External	18
Wait External	15
Counter-Demod (Common)	4
Subtotal	493
Servo Loops (5)	
Counter-Demod	4
Servo Power Amp	16
Servo Switch & Dir. Store	13
Encoder Electronics	29
Subtotal	62
Total Electronic/Electrical Failure Rate (x 10^{-6}):	
Parts Only	555
Other (Non-parts)	267
Overall System	822
Electronic/Electrical MTBF (hrs):	
Parts Only	1800
Other (Non-parts)	3745
Overall System	1217

Figure 5.7 *Reliability of electronic/electrical elements used in Unimate 2000 Series design*

MTBF for the Unimate system.

Once the reliability feasibility has been established, the hard work really begins. Aiming for an overall MTBF of 400 hours, Unimation Inc. set up a management system designed to bring individual components up to standard and assure statistically that the system, as shipped, will meet the overall goal. Figure 5.9 shows the reliability control points in the Unimate life cycle.

Since field experience is crucial to determining true reliability, the entire process of building toward this reliability includes placing machines in the field and feeding back the results of this experience into the reliability control system. In the case of the 2000 Series Unimate, the opening experience produced an MTBF of 145 hours and over the ensuing years of production, this MTBF was slowly brought up to 415 hours.

Failure classification	Failure rate (x 10^{-6})	MTBF (hours)
Part failures only:		
Electronic/Electrical	555	1800
Mechanical/Hydraulic	673	1485
Non-part failures:		
Electronic/Electrical	267	3745
Mechanical/Hydraulic	475	2100
System failures:		
Parts only	1228	815
Non-tolerance	742	1350
Combined	1970	508

Estimated reliability feasibility,
Unimate 2000: MTBF = 500 Hours

Figure 5.8 *Unimate system reliability estimate*

Long range outlook for reliability

The succeeding generations of industrial robots will become ever more sophisticated and that might be expected to portend a much reduced reliability potential. Fortunately, the reliability of solid state electronics continues to improve, and this counters the natural inverse correlation of reliability with complexity.

Nevertheless, with proliferating use of industrial robots in the factories and with more intimate interlocks between robots and factory information systems, it will become more and more difficult to maintain satisfactory uptime in the complete manufacturing process. It seems that the touchstone to minimizing downtime in the fully automated factory will be found in diagnostic monitoring systems which will pinpoint trouble spots instantaneously. Even in the face of deterioration in MTBF, really significant improvements in reaction time to a failure incident will result overall in acceptable factory uptime.

Maintenance needs and economics

The planning of robot maintenance can therefore draw upon a body of statistical information about the reliability of these machines according to hours worked and environmental conditions.

Field experience of reliability

In monitoring the continuing reliability of their robots, Unimation selects a sample of machines, chosen for their activity and spectrum of applications. Furthermore, the Unimate sample includes only those machines which are serviced by Unimation Inc personnel, to ensure consistency of data and to exclude those breakdowns which might result from a manufacturer's own maintenance shortcomings. In Unimation's reliability analysis it is assumed that all components have a constant failure rate. This simplification does not take into account wear and time-dependent degradation of performance. Data has to be watched for evidence of deterioration in the MTBF, which would suggest that a major overhaul is necessary. Unimation's experience indicates that deterioration of reliability is very much dependent upon the application, but seems to become significant after operating periods of between 8,000 and 15,000 hours. That is equivalent to something between four and seven man-shift years.

The discussion so far has been centred on MTBF, but it is well to consider also downtime. Four hundred hours was chosen by Unimation as a reasonable MTBF when speculating on acceptable downtime. Assuming that all field service is done by their personnel, that all their robots are working on a two shift basis, and that they can always offer next-day service, then the most likely downtime per incident that Unimation could expect would be 8 hours. This is 2% of the operating time, given an MTBF of 400 hours.

Of course, the situation is more complex. There is a variety of opportunities for minimizing the impact of downtime. For one thing, if the user has his own trained maintenance personnel, he should be able to react to a failure without having to await the arrival of the robot supplier's personnel. So too, even where training of a customer's personnel has been minimal, it is often possible to get a machine back on stream by telephoning the robot manufacturer. The user describes the breakdown symptoms, and the expert robotics engineer can attempt a remote diagnosis and suggest a prescribed course of treatment for the sick robot.

Maintenance economics

Unimation Inc. usually recommends that there be an eventual potential for at least three industrial robots at any single plant location. A trained maintenance man will not be effectively utilized until there is a minimum of three robots for which he is responsible. Exceptions, however, include cases in which risk-control concerns were dominant or in which the productivity gains achievable with one or two robots would more than off-set the expense of a specially trained employee.

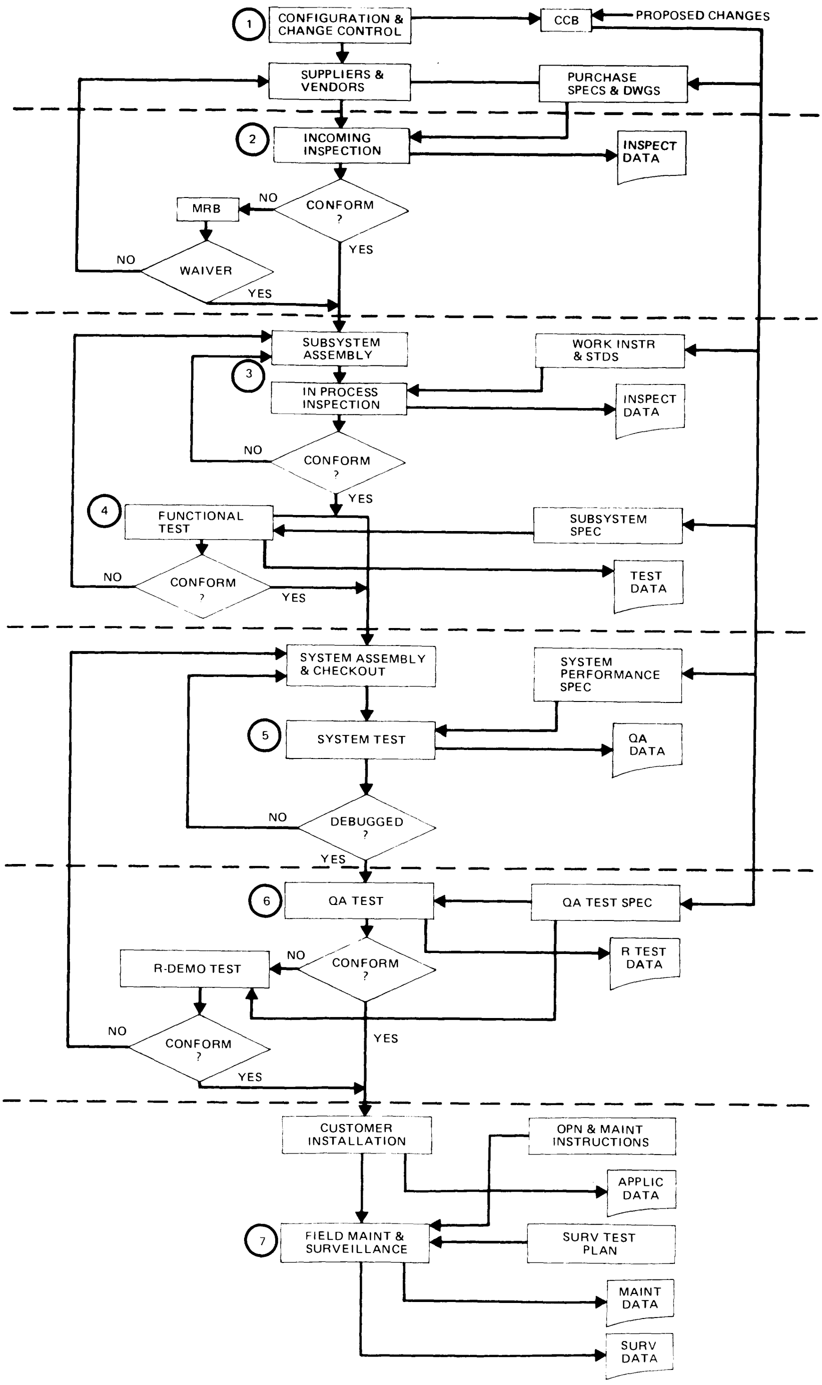

Figure 5.9 *Reliability control points in the Unimate life cycle*

Manufacturers of general-purpose industrial robots operate customer training programs or can arrange service contracts.

High cost inflation makes it unwise to try and give any absolute indication of maintenance costs. A more permanent approach is to compare the maintenance costs for robots with their cost of acquisition. This is the approach commonly used for factory automation in the automotive industry, where the annual maintenance costs are characteristically some 10% of the plant acquisition costs. For a Unimate robot working two shifts (4,000 hours) the annual maintenance works out at about 11% of average acquisition cost.

Under ideal circumstances, the user who has a multiplicity of robots in his plant can organize his own trained maintenance personnel. He is able to invest in the robot manufacturer's diagnostic test instruments (where these are offered for sale) and he can afford to build up a sensible stock of replacement parts, commensurate with the size of the robot population in his plant. Under such conditions the MTBF-downtime-maintenance pattern can be optimized.

Figure 5.10 shows a portion of the Unimate line in the Lordstown plant of General Motors. This plant hardly ever calls upon Unimation Inc. and all of its service is performed by blue-collar workers. Remarkably, with 26 machines on the line, downtime of the entire line amounts to only 6 minutes per shift. With an MTBF of 400 hours and 26 machines in the system, we can expect a robot failure incident every 15 hours. If the line were to be shut down upon every robot failure, it

Figure 5.10 *The Unimate line at General Motors' Lordstown plant*