Chapter 3

Programmable Automation Technologies

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Summary

This chapter is both a primer on programmable automation (PA) tools and their potential applications in manufacturing, and an assessment of the important problems and directions for development of the technologies. As defined here, programmable automation includes computer-aided design (CAD); computer-aided manufacturing tools—e.g., robotics, numerically controlled (NC) machine tools, flexible manufacturing systems (FMS), and automated materials handling (AMH); and computer-aided techniques for management—e.g., management information systems (MIS) and computer-aided planning (CAP). When systems for design, manufacturing, and management are used together in a coordinated system, the result is computer-integrated manufacturing (CIM).

The context for this analysis is primarily discrete manufacturing, as opposed to continuous-process industries such as chemicals or paper. Discrete manufacturing includes a wide range of traditional metalworking industries (e.g., automobiles and farm equipment) as well as other industries which are not primarily metalworking (e.g., electronics). Of particular note is that a great many of the products of discrete manufacturing are made in batches of perhaps a few dozen to a few hundred units. Because of this, it is often not economical to use single-purpose, automated machines (known as "fixed" or "hard" automation) to manufacture the product. In such an environment, programmable automation is potentially very useful.

The essential difference between conventional factory machines and programmable automation is the latter's use of information technology to provide machine control and communication. The use of computers and communications systems allows these machines to perform a greater variety of tasks than fixed automation can perform, and to automate some tasks which previously necessitated direct human control.

Programmable automation can respond to some of the central problems of manufacturing. These include enhancing information flow, improving coordination, and increasing efficiency and flexibility (defined as both the range of products and volume of a specific product which a factory can economically produce). By using programmable automation to address these problems, manufacturers hope to increase their productivity and control over the manufacturing process.

Though labor savings seem to be the most obvious benefit of automation, savings through more efficient use of materials may be more significant in many manufacturing environments. In particular, flexible manufacturing systems can reduce waste, reduce levels of finished product inventory, and reduce the manufacturer's substantial investment in the products that are in various stages of completion, known as "work in process."

Some of the technical factors which hold back PA's potential uses in manufacturing include relatively cumbersome programing languages, a general level of technical immaturity in many areas of the technologies, long-established organizational barriers in industry (e.g., between manufacturing and design engineers), and the embryonic nature of efforts to maximize the effectiveness of man-machine interactions.

Nevertheless, the technologies appear to be quite adequate technically for the vast majority of near-term applications; there seems to be a significant backlog of available tools which manufacturers have only begun to exploit.

The use of PA tools in integrated systems–e.g., FMS or CIM—is much more powerful than their use for a single task or process. Such integration not only magnifies the productivity and efficiency benefits of PA, but also tends to induce changes in all parts of the factory. Management strategies, product designs, and materials flow all change to best make use of such integrated systems.

Many industrialists have a vision of CIM that includes maximum use of PA tools and coordination between them, with few if any human workers. Others downplay CIM as a revolutionary change and emphasize that factories will adopt automation technologies as appropriate. It may not be appropriate (or eco nomical) to remove all or most humans from many factories. In any case, the widespread use of CIM and virtually unmanned factories are unlikely to arise before the turn of the century.

Principal themes in the future development of PA technologies include increasing their versatility and power, enhancing their capability to operate without human intervention, and developing the ability of the tools to be integrated. Researchers and industry spokesmen report progress in virtually all the fundamental technical areas, although many of the currently identified problems in programmable automation are complex enough to keep researchers busy for many years to come. According to many experts, the 1990's may bring many major technical advances which could significantly expand the range of problems to which programmable automation can be applied.

Introduction

The purpose of this chapter is to describe the technologies that together comprise "programmable automation, " and to evaluate their usefulness for manufacturing. In addition, the chapter examines how the technologies are evolving and what can be expected for the capabilities and applications of these tools.

Programmable automation refers to a family of technologies that lie at the intersection of computer science and manufacturing engineering. "Programmable' means that they can be switched from one task to another with relative ease by changing the (usually) computerized instructions; "automation" implies that they perform a significant part of their functions without direct human intervention. The common element in these tools that makes them different from traditional manufacturing tools is their use of the computer to manipulate and store data, and the use of related microelectronics technology to allow communication of data to other machines in the factory.*

There are three general categories of functions which these tools perform-they are used to help design products, to help manufacture (both fabricate and assemble) products on the factory floor, and to assist in management of many factory operations. Table 5 outlines the principal technologies included in these categories, each of which will be described in the next section.

*Although "programmable automation" is less common than some of the other terms used to describe automation technologies, it is a relatively simple and unambiguous term for the tools discussed here. "CAD/CAM" (computer-aided design/computer-aided manufacturing) is a catch-all term used in industry journals and popular articles to refer to a set of technologies similar to the set defined here as programmable automation. However, CAD/CAM is also used to describe some specific computer-aided design systems, or to denote the integration of computer-aided design and manufacturing. Because of this ambiguity, the term will not be used here. "Robotics" is another term that is sometimes used in a broad sense to mean not only robots but the whole family of automation tools.

Table 5.—Principal Programmable Automation Technologies

1. Computer-aided design (CAD)
- A. Computer-aided drafting
- B. Computer-aided engineering (CAE)

II. Computer-aided manufacturing (CAM)
- A. Robots
- B. Numerically controlled (NC) machine tools
- C. Flexible manufacturing systems (FMS)
- D. Automated materials handling (AMH) and automated storage and retrieval systems (AS/RS)

III. Tools and strategies for manufacturing management
- **A. Computer-integrated manufacturing (CIM)**
- **B. Management information systems (MIS)**
- **C. Computer-aided planning (CAP) and computer-aided process planning (CAPP)**

NOTE: Bold type indicates technologies on which this report concentrates
SOURCE Off Ice of Technology Assessment

The three categories of automation technologies-tools for design, manufacturing, and management-are not mutually exclusive. In fact, the goal of much current research in automation systems is to break down the barriers between them so that design and manufacturing systems are inextricably linked. However, these three categories are useful to frame the discussion, particularly since they correspond to the organization of a typical manufacturing firm.

Further, this report does not attempt to cover each of the technologies in equal detail. It concentrates on those five which appear in bold type in table 5 because they are the core technologies of PA and their potential uses are most extensive.

Discrete Manufacturing

Some background about manufacturing is important to provide a context for assessing the usefulness of these tools. Programmable automation can affect many kinds of industry. This report focuses on PA applications for discrete manufacturing-the design, manufacture and assembly of products ranging from bolts to aircraft. The report does not systematically cover nonmanufacturing applications such as architecture, or continuous-process manufacturing-e.g., chemicals, paper, and steel. Other recent OTA reports have examined technological changes affecting process industries.[1]

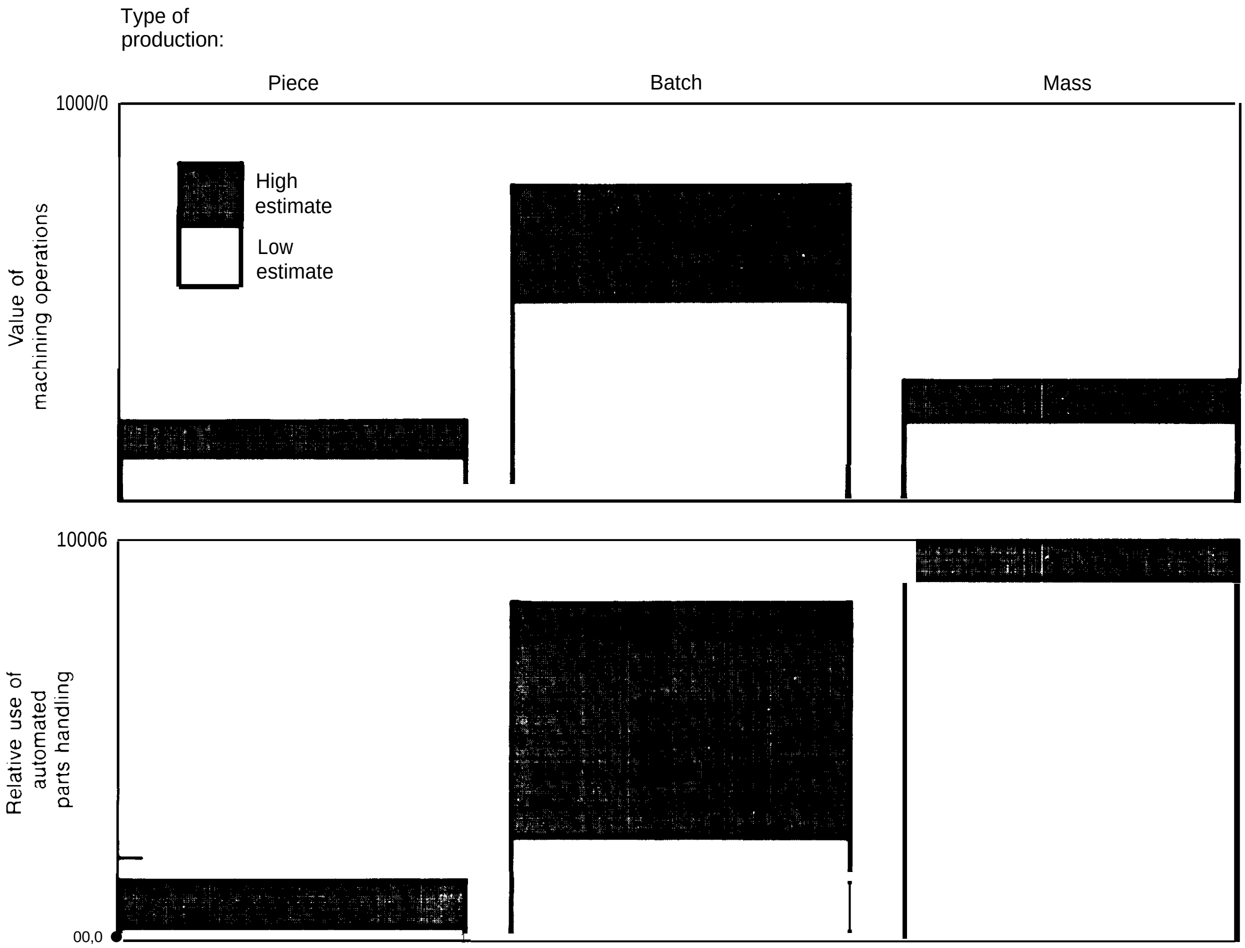
Electronics manufacturing industries do not fit neatly into a discrete v. process classification. Some areas, particularly the fabrication of semiconductors, most resemble continuous-process manufacturing. Other portions such as circuit board assembly are more discrete. Because electronics industries have been leaders among metalworking firms in both producing and using computerized factory automation, they play a key role in this report.

To many industrialists, discrete manufacturing means metalworking for mechanical applications-shaping, forming, and finishing metals into usable products such as engine blocks. However, an increasing proportion of mechanical parts manufacturing involves plastics, fiber composites, or new, durable ceramics. These new materials both enable new production processes and are themselves affected by automation technologies.

One way in which discrete manufacturing plants can be categorized that is especially relevant to automation applications is the voiume of a given part that they produce. As figure 1 indicates, discrete manufacturing represents a continuum from piece or custom production of a single part to mass production of many thousands. Although many people are most familiar with mass-production factories, with their assembly and transfer lines, it is estimated that mass production accounts for only 20 percent of metalworking parts pro-

‘Cf. *U.S. Industrial Competitiveness: A Comparison of Steel, Electronics, and Automobiles* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, OTA-ISC-135, July 1982); *Technology and Steel Industry Competitiveness* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, OTA-M-1 22, June 1980).

Figure 1.—Characteristics of Metalworking Production, By Lot Size



		Piece	Batch	Mass
Typical lot size	Large complex part	1-1o	10-300	Over *200*
	Small simple part	1-300	300-15,000	Over 10,000
Typical products		Aircraft, large turbines, centrifuges	Marine engines, large electric motors, tractors	Autos, fasteners, small appliances
Typical machines		Manual machine tools, or stand-alone numerically controlled (NC) machine tools	NC machine tools with automated part-handling machining cell flexible manufacturing system	Transfer lines, dedicated or special machines

SOURCE Machine Tool Task Force Technology of *Machine Took.* October 1980 duced in the United States, while 75 percent are made in a "batch" environment.[2] The definition of a "batch" varies according to the complexity of the part and the characteristics of the industry. A common characteristic of batch manufacturing is that there is not enough volume to justify specialized machines (known as "hard automation") to automatically produce the part. The direct labor involved in fabricating products in batches is relatively high (as shown in fig. 1), and constitutes a large proportion of the cost of the item. These characteristics of batch manufacturing—its prevalence, and its low level of automation and correspondingly high level of labor content—are important because they suggest a broad range of uses for programmable automation.

The Manufacturing Process

Figure 2 illustrates the organization of a hypothetical metalworking manufacturing plant. Most of the elements in this diagram are present in some form in each plant, although factories are tremendously varied in size, nature and variety of products, and production technologies. One automobile factory in New Jersey, for example, assembles 1,000 cars per day in two models (sedan and wagon) with 4,000 employees; a small Connecticut machine shop, by contrast, employs 10 people to make hundreds of different metal parts for aircraft and medical equipment, typically in batches of approximately 250.[3]

As illustrated in figure 3, the manufacturing process usually begins when management decides to make a new product based on information from its marketing staff, or (in the case of the many factories which produce parts of other companies' products) management receives a contract to produce a certain part. Management sends the specifications for the size, shape, function, and desired performance of the product to its design engineering staff, who are responsible for developing the plans for the product.* In most companies, design engineers make a rough drawing of the product, and then draftsmen and design detailers are responsible for working out the detailed shapes and specifications.

In some discrete manufacturing firms, design may be undertaken at a distant location, or at a different firm. Automobiles, for example, are designed at central facilities, and the component subassemblies-e. g., bodies, transmissions, engines-are produced in plants all over the world.

The design of a product, especially a product of some complexity, involves an intricate set of tradeoffs between marketing considerations, materials and manufacturing costs, and the capabilities and strengths of the company. The number of choices involved in design is immense. Determining which of many alternative designs is "best" involves making choices among perhaps 100,000 different materials, each with different characteristics of strength, cost, and appearance; it also involves choices between different shapes and arrangements of parts which will differ in ease of fabrication and assembly (sometimes called "manufacturability' and in performance.

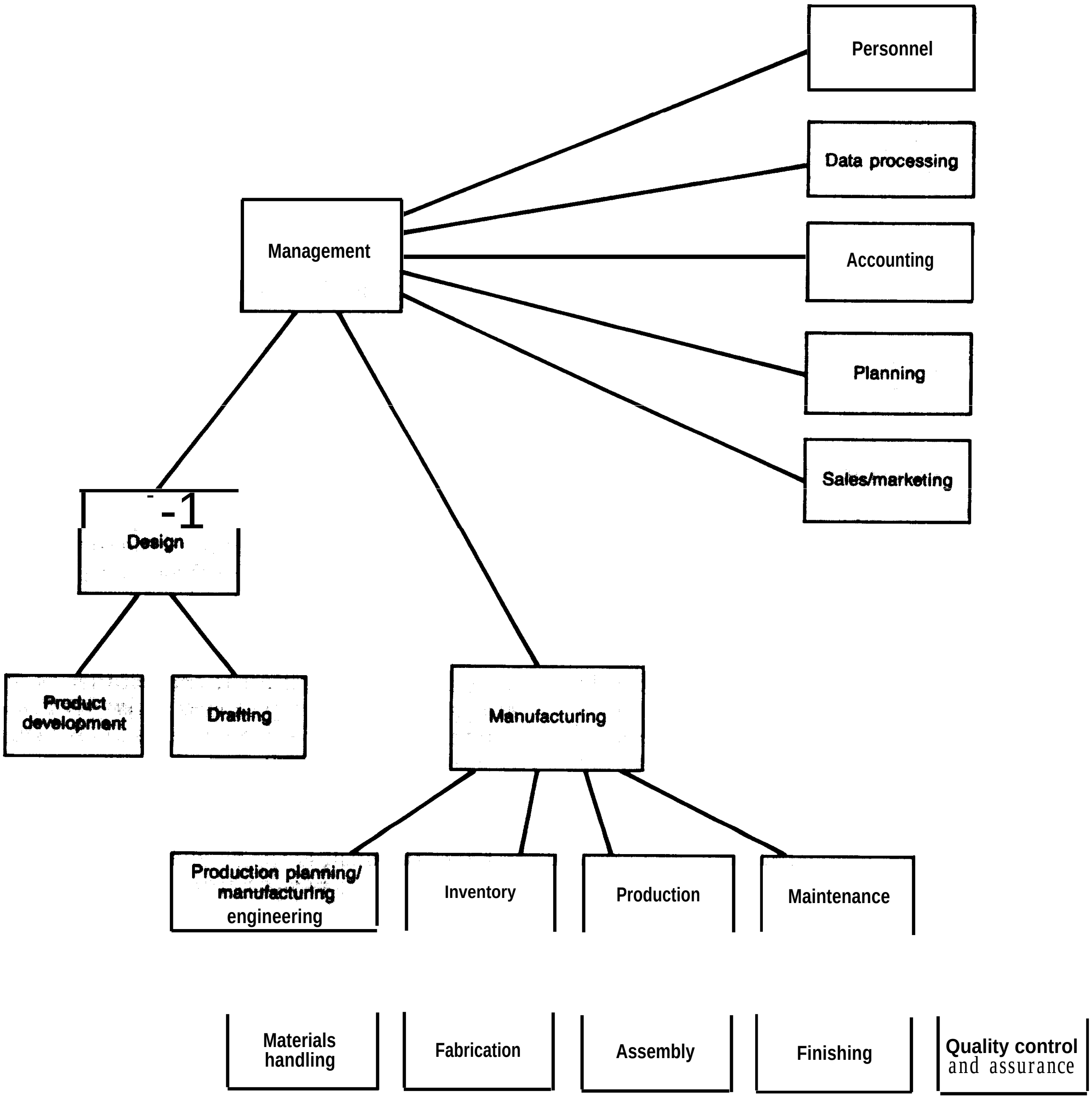
From the design, the production engineering staff determines the "process plan' 'machines, staff, and materials which will be used to make the product. Production planning, like design, involves a set of complex choices. In a mass production plant that manufactures only a few products, such as the auto plant described above, production engineering is a relatively well-structured problem. With high volumes and fairly reliable expectations about the products to be made, decisions about appropriate levels of automation, for example,

[2]M.E. Merchant, "The Inexorable Push for Automated Production, " *Production Engineering*, January 1977, pp. 44-49. This 75 percent figure has become something of a legend in the metalworking industry largely through Merchant's writings, though he notes that he has lost track of the original reference for the statistic. While it is hard to substantiate given the diversity of metalworking industry, Merchant and other industry experts cite it as a good rough estimate. Personal communication, M. E. Merchant, Nov. 7, 1983.

[3]OTA work environment case studies.

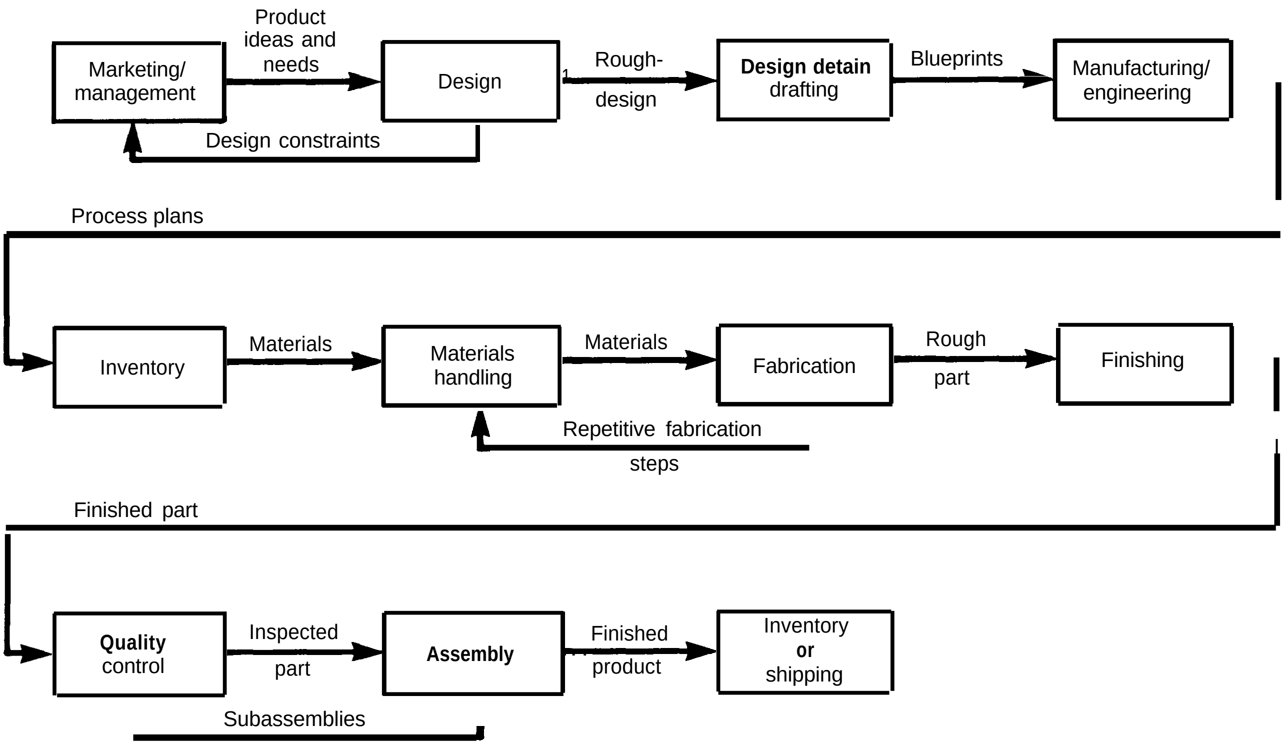
*In this description, as in the rest of the chapter, titles such as "manager," "design engineer, " or "draftsman" indicate the person who performs these functions. In an actual company the roles may be less distinct, and boundaries between them frequently changing.

Figure 2.—Organizational Diagram of a Manufacturing Firm



SOURCE Office of Technology Assessment

Figure 3.—Steps in the Manufacturing Process (Simplified)



SOURCE Office of Technology Assessment

are relatively straightforward. On the other hand, for a small "batch" manufacturer such as the Connecticut machine shop referred to above, production engineering decisions can be rather chaotic. Such an environment involves almost continuous change in the number and types of parts being produced (size, shape, finish, material), the tools and levels of skill needed to produce them, and unpredictables such as machine breakdowns and inventory control problems.

The steps in production are immensely varied, but most products typically require the following:

1. *Materials handling.* —Materials are brought from inventory to processing stations, and from one station to another. Wheeled carts, forklift trucks, or conveyors are typically used for this purpose. Early in the production process, large parts are mounted on a pallet or fixture to hold them in place and facilitate materials handling.
2. *Fabrication.* —There is a tremendous variety of fabrication processes. Plastic and ceramic parts are extruded or molded; layers of composite fiber material are treated and "laid up." The most common sequence for three-dimensional (3-D) metal parts is casting or forging, followed by machining.

Figure *4* illustrates the basic machining processes which are the core of metalworking. The shape and size of the metal part, as well as the desired finish and pre cision, determines the machine to be used. Some machine tools, such as lathes, are designed for cylindrical parts, e.g., drive shafts or rotors. Others, such as planers, are designed for prismatic parts with basically flat outer surfaces, e.g., engine blocks. Abrasive cutting of metal produces "chips," the metal shavings re-

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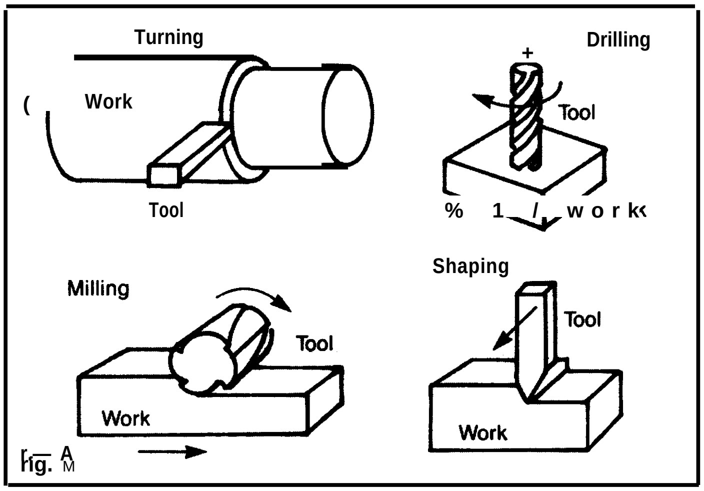
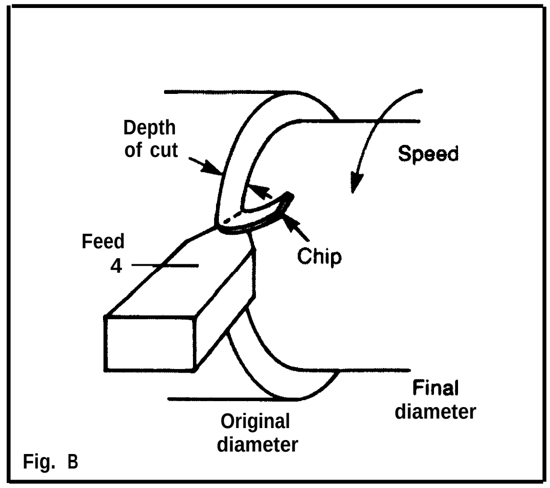
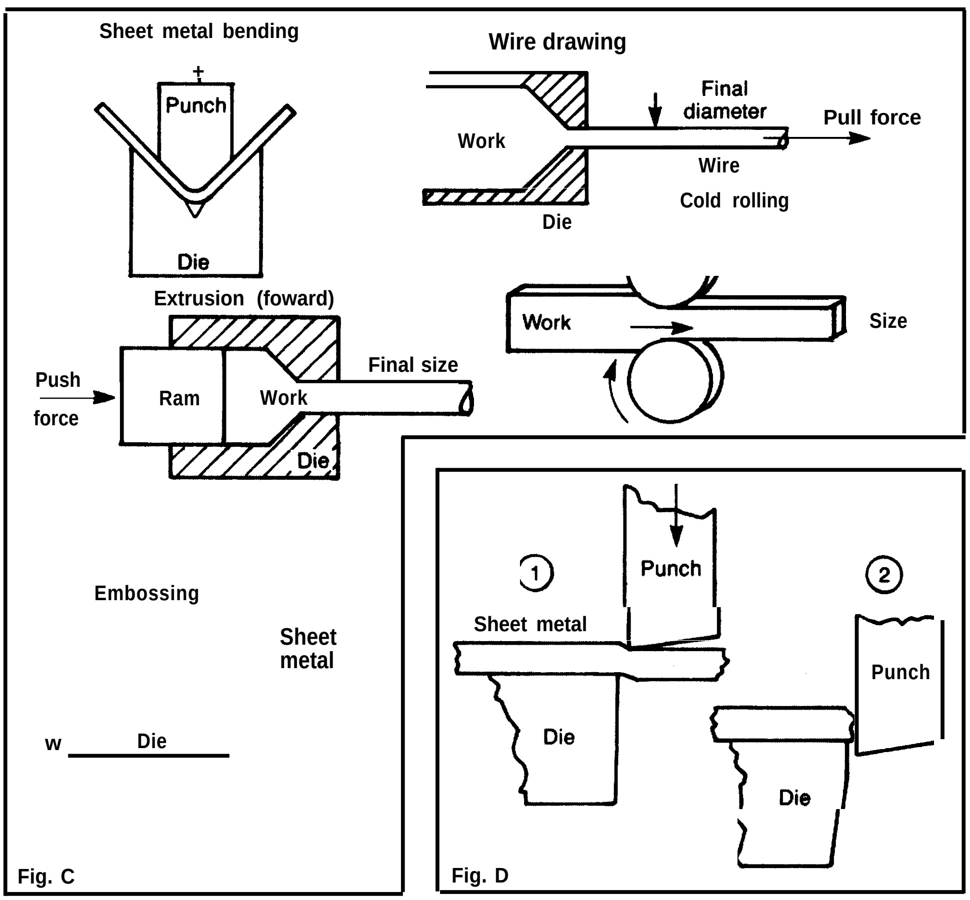
Figure 4.—Fundamental Operations in Metalworking



[A] The four basic maching processes can, between them, theoretically produce any contour on a workplace Although the processes are old, they are the foundation of metalworking and are being made more productive **and accurate**



[B] In any of the basic maching processes, speed, feed, and depth of cut determine productivity The three variables are shown here for turning on a lathe



[C] Forming operations bend. squeeze, or stretch metal, imparting new sizes or shapes. or both

[D] Shearing deforms metal beyond Its breaking point, thereby separating one portion of a metal sheet from another.

SOURCE M P Groover Fundamental Operations *EEE Spectrum vol* 20 No 5 May 1983 Reprinted with permission of /EEE Spectrum IEEE moved from the part, and these chips must be frequently removed from the machine and recycled or disposed.

Simple parts may be machined in a few minutes; large, complex ones such as ship propellers may take up to a few days. The complexity of these parts is primarily a function of their geometry–a propeller, for example, has continuously varying and precise curves. Similarly, the complexity of a prismatic part depends on the number of edges and required tolerances —i.e., the amount a part or surface can vary from its specified dimensions. Complex parts usually require machining on more than one machine tool. Including all machining operations, the total time from metal "blank" to finished part may vary from a few minutes to a few weeks. The partially completed "workpieces" awaiting further machining, finishing, assembly, or testing are known as work-in-process inventories, and often represent a substantial investment for the manufacturer.

Finally, there are several kinds of metal parts which are not machined. These include sheet metal parts, which are stamped and/or bent in sheet-metal presses, and parts made by "powder metallurgy, " a technology for forming metal parts in near-final shape by applying extreme pressure and heat to metal powder.

3. Finishing. -Many fabrication processes leave "burrs" on the part which must be removed by subsequent operations. In some cases, parts are also washed, painted, polished, or coated.
4. *Assembly.–The* finished parts are put together to produce a final product or, alternatively, to produce "subassemblies" which are portions of the final product. In most factories assembly is still primarily a manual activity, although this phase of manufacturing is receiving increased attention, ranging from design strategies that minimize and simplify assembly tasks to automation of the tasks themselves.
5. *Quality assurance and* control.–There are many quality strategies. They can be divided roughly into those that take place before or during fabrication and assembly (quality assurance or QA) and those that take place after a product or subassembly is complete (quality control or QC). Quality has been receiving increasing attention in industrial literature and discussions, although the extent to which companies are actually paying more attention to quality on the factory floor is uncertain. There appears to be a movement toward QA as opposed to QC in order to enhance quality and prevent the production of faulty products, as opposed to detecting flaws after production. Strategies for QA range from "quality circles, " in which a team of employees helps address production issues which affect quality, to in-process measurement of products as they are manufactured. In the latter, developing problems in production equipment can sometimes be detected and corrected before the machine makes a bad part. Most complex products are produced with some combination of QA and QC.

   Strategies for attaining the more traditional quality control vary widely according to the nature and complexity of the part. The dimensions of mechanical products can be measured, either with manual instruments or with a Coordinate Measuring Machine or laser measurement device; or the product can be compared to one of known quality or to a master gage. Electronic products can be tested with other electronic devices or probes.

This brief outline of the manufacturing process suggests some of the key problems in manufacturing. Underlying each of these problems are the central concerns for any business, those of minimizing cost and risk. The problems include:

- *Information flow.* — In any company, small or large, the amount of information that must flow between and among design, manufacturing, and management staff is staggering. For example, in a design process involving several teams of people, how does one make sure that all design and manufacturing personnel are working from the most up-to-date set of plans? How can staff get up-to-date information on the status of a particular batch of parts, or the performance of a particular machine tool or manufacturing department? How can the company keep track of work-in-process and other inventory?

- *Coordination.*– Beyond merely obtaining information in a timely fashion, the company must use that information to determine how to effectively coordinate its operations. One set of such issues involves coordination of design and production efforts. How can one design products which can be manufactured most efficiently with a given set of tools? How can one minimize the number of parts in order to facilitate assembly? Another set of coordination issues arises on the factory floor itself. What is the most efficient way to allocate machines and personnel? How does one adapt the schedule when conditions inevitably change (raw materials don't arrive, production is slower than expected, etc.)?
- *Efficiency.* —Given a large set of choices regarding tools, personnel, and factory organization, a company generally seeks to make the most products using the fewest resources. This involves concerns such as: How can the company minimize expensive work-in-process inventories? How can manufacturers maximize the percentage of time spent making parts, as opposed to moving them, repairing or setting up machines, and planning? How cm the use of expensive capital equipment be maximized? Finally, quality issues within the production process can have a large impact on efficiency. How can manufacturers maximize the number of products made right the first time, and hence minimize scrap, rework to correct manufacturing errors, and testing?
- *Flexibility.* –Increasingly, issues of flexibility and responsiveness in the manufacturing enterprise are prominent for manufacturers, especially for traditional "mass production" plants. Flexibility is defined here as the range of products and the range of volumes of a specific product which a plant cm economically produce. Increased levels of competition, shorter product cycles, and increased demands for customized products are some of the reasons for an emphasis on flexibility. This concern raises such questions as: How can the turnaround time for design and manufacture of a product be reduced? How can the "setup" time for producing a new product be reduced? What is the optimum level of technology for both economy of production and maximum flexibility?

Programmable automation offers improvements in each of these four key areas of manufacturing by applying computerized techniques to control tools of production, to gather and manipulate information about the manufacturing process, and to design and plan that process. Further, the use of PA promises for many manufacturers an increase in their de gree of control over the enterprise. Many industrialists argue that the more closely manufacturing processes are tied to one another, and the more information is readily available about those processes, the less chance there is for human error or discretion to introduce unknown elements into the operation. Such control is much harder to realize than it appears in theory. The issue of control will be a recurrent theme in this and subsequent chapters of this report.

In summary, programmable automation can help make factories "leaner" and more responsive, hence reducing both costs and risks in manufacturing. It is not, however, a panacea for problems in manufacturing. Each factory has different appropriate levels of automation, and there are technical and organizational barriers to implementing programmable automation most effectively. PA's capabilities and characteristics from a technical standpoint will be elaborated in the rest of this chapter, beginning with functional descriptions of the technologies themselves. The organizational and social concerns will be addressed at length in following chapters of the report.

Functional Descriptions

This section briefly describes the operation of each programmable automation technology and its applications in manufacturing.

Computer-Aided Design (CAD)

In its simpler forms, CAD is an electronic drawing board for design engineers and draftsmen. Instead of drawing a detailed design with pencil and paper, these individuals work at a computer terminal, instructing the computer to combine various lines and curves to produce a drawing of a part and its specifications. In its more complex forms, CAD can be used to communicate to manufacturing equipment the specifications and process for making a product. Finally, CAD is also the core of computer-aided engineering, in which engineers can analyze a design and maximize a product's performance using the computerized representation of the product.

Photo credit Cincinnati Milacron Corp

A designer works on a two-dimensional part drawing at a CAD terminal. The "light pen, " held in his right hand, can be used to point to parts of the drawing and give commands to the computer

The roots of computer-aided design technology are primarily in computer science. CAD evolved from research carried out in the late 1950's and early 1960's on interactive computer graphics-simply, the use of computer screens to display and manipulate lines and shapes instead of numbers and text. As S. H. Chasen of Lockheed-Georgia describes the rationale behind this research: "The ability of the computer to spill out reams of geometric data had outpaced our ability to cope with it."[4] SKETCHPAD, funded by the Department of Defense (DOD) and demonstrated at Massachusetts Institute of Technology in 1963, was a milestone in CAD development. Users could draw pictures on a screen and manipulate them with a "light pen "-a pen-shaped object wired to the computer which locates points on the screen. Such early systems were expensive prototypes and required most of the computing power of the then-largest computers. As a consequence, most of the early users of CAD were aerospace, automobile, and electronics manufacturers.

Several key developments in the 1960's and 1970's facilitated the maturation of CAD technology. They included the continuing decrease in cost of computing power, especially with the development of powerful mini- and microcomputers, which were primarily a result of electronics manufacturers learning to squeeze more and more circuitry into an integrated circuit chip. Another important technological advance was the development of cheaper, more

[4]S. H. Chasen, "Historical Highlights of Interactive Computer Graphics, " Mechanical Engineering, November 1981, pp. 22-41.

efficient display screens. In addition, computer scientists began to develop very powerful programing techniques for manipulating computerized images.

How CAD Works. —There are various schemes for input of a design to the computer system, each with its advantages and disadvantages. Every CAD system is equipped with a keyboard, although other devices are often more useful for entering and manipulating shapes. The operator can point to areas of the screen with a light pen or use a graphics tablet, which is an electronically touch-sensitive drawing board; a device called a "mouse" can be traced on an adjacent surface to move a pointer around on the screen. If there is already a rough design or model for the product, the operator can use a "digitizer" to read the contours of the model into computer memory, and then manipulate a drawing of the model on the screen. Finally, if the part is similar to one that has already been designed using the CAD system, the operator can recall the old design from computer memory and edit the drawing on the screen.

CAD systems typically have a library of stored shapes and commands to facilitate the input of designs. There are four basic functions performed by a CAD system which can enhance the productivity of a designer or draftsman. First, CAD allows "replication," the ability to take part of the image and use it in several other areas of the design when a product has repetitive features. Second, the systems can "translate" parts of the image from one location on the screen to another. Third is "scaling, " in which CAD can "zoom in' on a small part, or change the size or proportions of one part of the image in relation to the others. Finally, "rotation" allows the operator to see the design from different angles or perspectives. Using such commands, operators can perform sophisticated manipulations of the drawing, some of which are difficult or impossible to achieve with pencil and paper. Repetitive designs, or designs in which one part of the image is a small modification of a previous drawing, can be done much more quickly through CAD. On the other hand, CAD can be cumbersome, especially for inexperienced users. Drawing an unusual shape maybe fairly straightforward with a pencil, but quite complex to accomplish using the basic lines and curves in the system's library.

The simplest CAD systems are two-dimensional (2-D), like pencil-and-paper drawings. And like sets of those drawings, they can be used to model 3-D objects if several 2-D drawings from various perspectives are combined. For some applications, such as electronic circuit design, 2-D drawings are sufficient. More sophisticated CAD systems have been developed in the past few years which allow the operator to construct a 3-D image on the screen, * a capability which is particularly useful for complex mechanical products.

Most CAD systems include a few CAD terminals connected to a central mainframe or minicomputer, although some recently developed systems use stand-alone microcomputers. As the operator produces a drawing, it is stored in computer memory, typically on a magnetic disk. The collection of digitized drawings in computer storage becomes a design data base, and this data base is then readily accessible to other designers, managers, or manufacturing staff.

CAD operators have several options for output of their design. All systems have a plotter, which is capable of producing precise and often multicolor paper copies of the drawing. Some systems can generate copies of the design on microfilm or microfiche for compact storage. Others are capable of generating photographic output. In most cases, however, the paper output from CAD is much less important than it is in a manual design process. More important is the fact that the design is stored on a computer disk; it is this version which is most up-to-date and accessible, and

*In a practical sense, any image on a computer screen is two dimensional, The difference between a "3-D" image as discussed here and any other 2-D drawing that appears three-dimensional (e.g., a painting, a photograph or any drawing with perspective) is that this image, unlike a paper drawing, can be manipulated as if it were a real 3-D object. For example, the operator can instruct the CAD system to rotate the object, and he/she then sees another face of the object,

Illustrafion credit Computervision Corp.

The designer has removed a section of this three-dimensional CAD image in order to better visualize part relationships and assembly information

which will be modified as design changes occur.

The CAD systems described above are essentially draftsmen's versions of word processors, allowing operators to create and easily modify an electronic version of a drawing. However, more sophisticated CAD systems can go beyond computer-aided drafting in two important ways.

First, such systems increasingly allow the physical dimensions of the product, and the steps necessary to produce it, to be developed via the computer and communicated electronically to computer-aided manufacturing equipment. Some of these systems present a graphic simulation of the machining process on the screen, and guide the operator step-by-step in planning the machining process. The CAD system can then produce a tape which is fed into the machine tool controller and used to guide the machine tool path. Such connections from computer-aided design equipment to computer-aided manufacturing equipment shortcut several steps in the conventional manufacturing process. They cut down the time necessary for a manufacturing engineer to interpret design drawings and establish machining plans; they facilitate process planning by providing a visualization of the machining process; and they reduce the time necessary for machinists to interpret process plans and guide the machine tool through the process.

Second, these more sophisticated CAD systems serve as the core technology for many forms of computer-aided engineering (CAE). Beyond using computer graphics merely to facilitate drafting and design changes, CAE tools permit interactive design and analysis. Engineers can, for example, use computer graphic techniques for simulation and animation of products, to visualize the operation of a product or to obtain an estimate of its performance. Other CAE programs can help engineers perform finite element analysis-essentially, breaking down complex mechanical objects into a network of hundreds of simpler elements to determine stresses and deformations. Computerization in general made finite element analysis feasible for the engineer's use, while CAD systems make it significantly less cumbersome by assisting the engineer in breaking down the object into "elements.

Many of these analytical functions are dependent on 3-D CAD systems which can not only draw the design but also perform "solid modeling"—i.e., the machine can calculate and display such solid characteristics as the volume and density of the object. Solid-modeling capabilities are among the most complex features of CAD technology, and will be discussed in more detail in later sections of this chapter.

Applications. -At the end of 1983 there were an estimated 32,000 CAD workstations in the United States.[5]

Aerospace and electronics uses of CAD have always led the state of the art. For example, the Boeing Commercial Airplane Co., which began using CAD in the late 1950's, employed the technology extensively in the design of its new-generation 757 and 767 aircraft. Boeing uses CAD to design families of similar parts such as wing ribs and floor beams. CAD allows designers to make full use of similarities between parts so that redesign and redrafting are minimized. Moreover, CAD has greatly simplified the task of designing airplane interiors and cargo compartments, which are often different for each plane. Moving seats, galleys, and lavatories is relatively simple with CAD, and the system is then used to generate instructions for the machines which later drill and assemble floor panels according to the layout. Finally, Boeing uses CAD and related interactive computer graphics systems as the basis for computer-aided engineering applications such as checking mechanism clearances and simulating flight performance of various parts and systems.[6]

Computer-aided engineering has also become important in the automobile and aerospace industries, where weight can be a critical factor in the design of products. These industries have developed CAE programs which can optimize a design for minimum material used while maintaining strength.

Applications for the design of integrated circuits are similarly advanced. Very large-scale integrated (VLSI) circuits, for example, have become so complicated that it is virtually im-

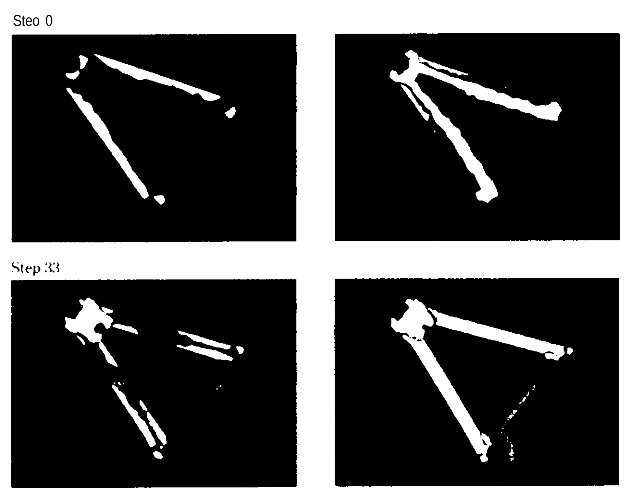


Illustration credit: General Motors Corp.

A computer-aided engineering system developed at General Motors Research Laboratories can help designers develop parts which are of minimum mass, yet are capable of performing under the structural loads. The CAE system tries to make the part thinner and lighter with each step; shading changes which appear on the computer screen show simulated stress levels within the design limits for this part

[5] Source: Dataquest.

[6] W. D. Beeby, (former) Director of Engineering Computing Systems, Boeing Commercial Airplane Co., "Applications of Computer-Aided Design on the 767" (Seattle: Boeing, 1983).

possible for a person to manually keep track of the circuit paths and make sure the patterns are correct. There is less need here for geometrically sophisticated CAD systems (integrated circuit designs are essentially a few layers of two-dimensional lines), and more need for computer-aided engineering systems to help the designer cope with the intricate arrangement of the circuit pattern. Such CAE programs are used to simulate the performance of a circuit and check it for "faults," as well as to optimize the use of space on the chip.[7]

CAD is also beginning to be used for non-aerospace mechanical design, and in smaller firms; these developments are being spurred on by the marketing of relatively low-priced "turnkey" systems—complete packages of software and hardware which, theoretically, are ready to use as soon as they are delivered and installed. While a standard and reasonably powerful system based on a minicomputer is typically in the $500,000 range, many smaller microcomputer-based systems have been introduced in the past year for under $100,000, in some cases for as low as $10,000 to $20,000. Very low-cost systems which run on common microcomputers have been introduced, and these have potential uses in a wide variety of firms which otherwise might not consider CAD (see ch. 7). The cost of custom-developed, specialized systems such as those described above for aerospace and electronics applications is harder to gauge but runs well into the millions of dollars.

[7]S. B. Newell, A. J. de Geus, and R. A. Rohrer, "Design Automation for Integrated Circuits, " Science, Apr. 29, 1983, pp. 465-471.

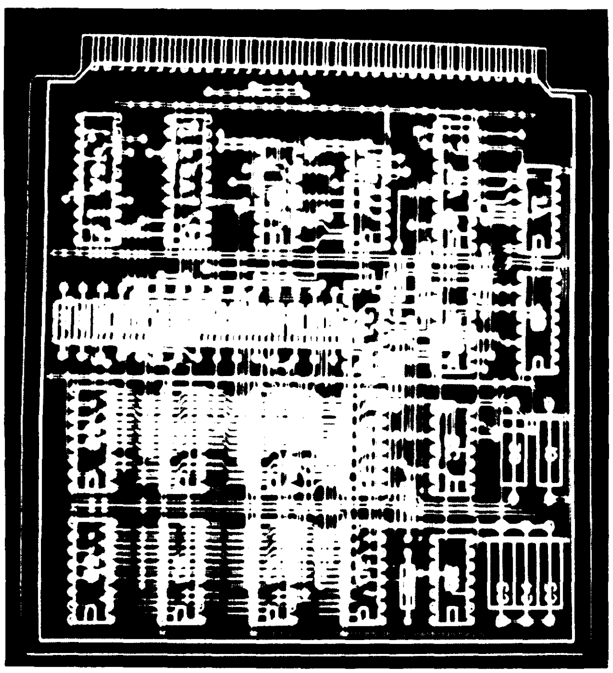


Photo *credit Computervision Corp*

CAD systems are used frequently in electronics industries to design and analyze complex circuit patterns

The potential advantage of CAD for large as well as small mechanical manufacturing firms is that it addresses several of the problems in manufacturing referred to at the beginning of this chapter. It facilitates use of previous designs, and allows design changes to be processed more quickly. Because CAD reduces the time necessary for many design tasks, it can also improve design by allowing designers to "try out" a dozen or a hundred different variations, where previously they might have been limited to building perhaps three or four prototype models. It also allows many drawings to be constructed more quickly, especially with an experienced CAD operator. Comparisons of design time with CAD range from 0.5 to 100 times as fast as manual systems, with 2 to 6 times as fast being typical. * For instance, Prototype and Plastic Mold Corp. in Middletown, Corm., is a small firm that uses CAD to design short-lived metal molds for plastic parts. The firm's president reported that designs could be produced with CAD roughly twice as fast as previously. For example, they received specifications for a plastic part mold by air express one Saturday morning, and planned to return the design drawings by air express that evening-a feat which, they reported, would have been impossible without CAD.**

Many of these represent comparisons of the time necessary for a very narrowly defined task, and exclude time necessary for related tasks on a CAD system such as setting up the machine, manipulating files, or recovering from a machine failure.

**OTA sit, visit, protype and Plastic Mold Corp., Middletown, Corm., June 3, 1983. One scientist has pointed out that the time savings would be even more striking if Prototype and

Other applications of CAD, though not directly connected to manufacturing, include mapping, architectural drawing and design, graphics for technical publishing, and animation and special effects in cinematography.

Computer-Aided Manufacturing (CAM) Technologies

Computer-aided manufacturing (CAM) is a widely used term in industrial literature, and it has various meanings. Here it is defined simply as those types of programmable automation which are used primarily on the factory floor to help produce products. The following sections provide functional descriptions of four CAM tools: robots, numerically controlled machine tools, flexible manufacturing systems, and automated materials handling systems.

Robots

Robots are manipulators which can be programed to move workplaces or tools along various paths. Most dictionary definitions describe robots as "human-like," but industrial robots bear little resemblance to a human. *

There is some controversy over the definition of a robot. The Japan Industrial Robot Association, for example, construes almost any machine that manipulates objects to be a robot (essentially including the "hard automation" mentioned earlier), while the oft-quoted Robotic Industries Association (RIA) definition** emphasizes that the robot must be flexible, or relatively easily changed from one task to another. The RIA definition thus excludes preset part-transfer machines used for decades as a part of largebatch and mass-production systems, whose path can be changed only by mechanically reworking or rearranging the device. Also excluded are "manual manipulators" or "teleoperators' '-devices directly controlled by a human such as those for remote handling of radioactive material.

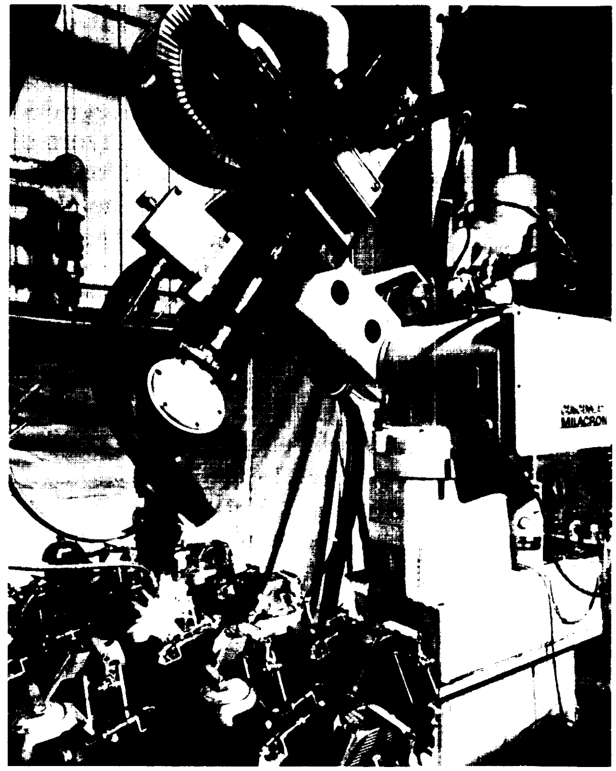


Photo credit Cincinnati Milacron Corp

A robot used for welding

As OTA observed in an earlier report on this subject,[8] industrial robots have a dual technological ancestry, emerging from: "l) industrial engineering automation technology, a discipline that stretches historically over a century; and 2) computer science and artificial intelligence* technology that is only a few decades old." Indeed, there is still a dichotomy

Plastic Mold's staff could have transmitted the design information by telephone computer links; such activities have begun to be feasible within the last few years.

*In this sense the technical usage of the term "robot" differs from its dictionary definition (and from its roots in literature, in particular Karel Capek's 1923 novel, *R. U.R. (Rossum's Universal Robots) A Fantastic Melodrama.* (Garden City, N. Y.: Doubleday, Page & Co., 1923). A robot which resembled a human would be an "android," in robotics parlance. Such a machine has not been designed, and there does not appear to be substantial movement toward human-like robots (except, perhaps for motion pictures and other entertainment purposes). Later sections of this chapter will discuss adding certain anthropomorphic characteristics and skills to robots.

● *RIA (a trade association of robot manufacturers, constaants, and users, formerly the Robot Institute of America) defines a robot as a "reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices, through variable programed motions for the performance of a variety of tasks. "

'*Exploratory Workshop on the Social Impacts of Robotics: Summary and Issues* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, OTA-BP-CIT-11, February 1982).

*Artificial intelligence research seeks to develop computer systems that can perform tasks which are ordinarily thought to require human intelligence.

Photo credit Cincinnati Milacron *Corp*

Robot used for loading and unloading a machine tool

among experts regarding the applications and research directions for robotics. Some emphasize the need for anthropomorphic capabilities in robots such as "intelligence," vision, and mobility, while others view robots as simply a more versatile extension of other manufacturing tools.

While it is uncertain to what extent artificial intelligence researchers will succeed in developing intelligent machines in the next few decades, it is certain that robots currently available, and those likely to be available in the next decade, neither look like humans nor have more than a fraction of the dexterity, flexibility, or intelligence of humans. A more accurate term for these machines might be "programmable manipulator. " Nevertheless it is clear that much of the great popular interest in robotics is rooted in the prevailing vision (or nightmare) of intelligent robots with human-like characteristics. Artificial intelligence will be discussed in more detail in the "Technical Trends and Barriers" section of this chapter.

How Robots Work.—There are three main parts of a typical industrial robot: the controller, manipulator, and end-effecter. The controller consists of the hardware and software—usually involving a microcomputer or microelectronic components—which guides the motions of the robot and through which the operator programs the machine. The manipulator consists of a base, usually bolted to the floor, an actuation mechanism-the electric, hydraulic, or pneumatic apparatus which moves the arm-and the arm itself, which can be configured in various ways to move through particular patterns. In the arm, "degrees of freedom"–basically, the number of different joints-determine the robot's dexterity, as well as its complexity and cost. Finally, the end-effecter, usually not sold as part of the robot, is the gripper, weld gun, or other tool which the robot uses to perform its task.

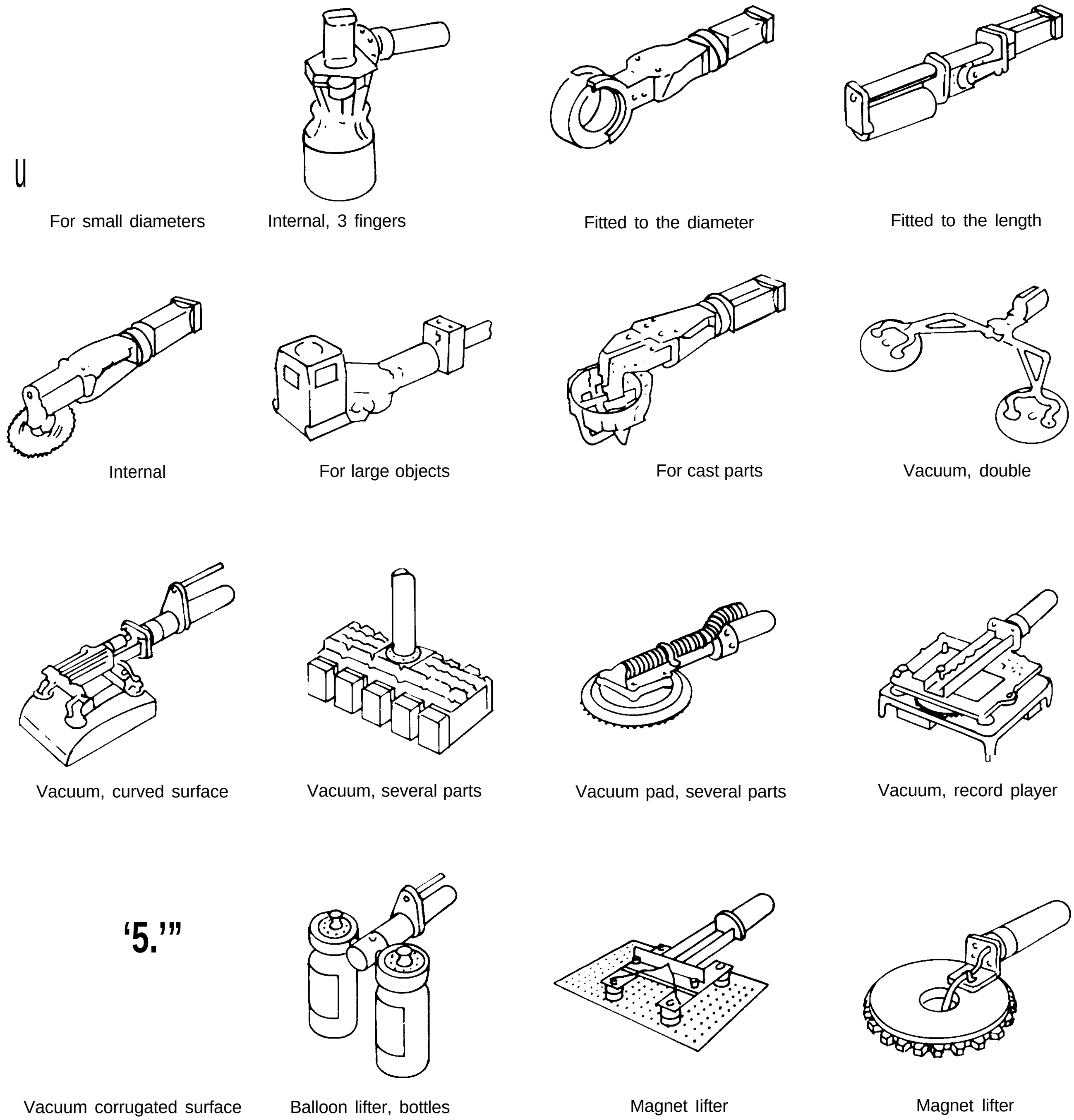
The structure, size, and complexity of the unit varies depending on the application and the industrial environment. Robots designed to carry lighter loads tend to be smaller, and operated electrically; many heavier units move their manipulator hydraulically. Some of the simpler units are pneumatic. Some of the heaviest material-handling robots and the newer light-assembly robots are arranged gantry-style, that is, with the manipulator hanging from an overhead support. A few robots are mobile to a limited degree, e.g., they can roll along fixed tracks in the floor or in their gantry supports.

Similarly, there is a great variety of end-effectors, particularly grippers, most of which are customized for particular applications. Grippers are available to lift several objects at once, or to grasp a fragile object without damaging it (see fig. 5).

Programing.-There are essentially two methods of programing a robot. The most commonly used method is "teaching by guiding. " The worker either physically guides the robot through its path, or uses switches on a control panel to move the arm. The controller records that path as it is "taught." Just beginning to emerge is "offline programing," where an operator writes a program in computer language at a computer terminal, and directs the robot to follow the written instructions.

Each method of programing has advantages that depend on the application. Teaching by guiding is the simplest and is actually superior for certain operations: spray painting is an example where it is useful to have the operator guide the robot arm through its path, because of the continuous, curved motions usually necessary for even paint coverage. However, teaching by guiding offers minimal ability to "edit" a path—i.e., to modify a portion of the path without re-recording the entire path. Offline programing is useful for several reasons: 1) production need not be stopped while the robot is being programed; 2) the factory floor may be an inhospitable environment for programing, whereas offline programing can be done at a computer terminal in an office; 3) as computer-aided manufacturing technologies become more advanced and integrated, they will increasingly be able to automatically generate robot programs from design and manufacturing data bases; and 4) an offline, written program can better accommodate more complex tasks, especially those in which "branching" is involved (e.g., "if the part is not present, then wait for the next cycle"). These branching decisions require some kind of mechanism by which the robot can sense its external environment. However, the vast majority of robotic devices are unable to sense their environment, although they may have internal sensors to provide feedback to their controller on the position of the arm joints.

Figure 5.—Sample Robot Grippers



SOURCE Tech Tran Corp Industrial *Robots A Summary and Forecast* 1983

Sensors.–Devices for sensing the external environment, while often used in conjunction with robots, are a growing technology in themselves. The simplest sensors answer the question, "Is something there or not?" For example, a light detector mounted beside a conveyor belt can signal when a part has arrived because the part breaks a light beam. Somewhat more complex are proximity sensors which, by bouncing sound off objects, can estimate how far away they are. The technology for these devices is fairly well-established. But the most powerful sensors are those which can interpret visual or tactile information; these have just begun to become practical.

Ideally, vision sensors could allow a robot system to respond to changes in its environment, and inspect products, as well as or better than a human could. However, using computers to process images from a video camera has proven to be an extraordinarily difficult programing task. Routine variations in lighting, the complexity of the everyday environment, common variations in shape or texture, and the difference between a 2-D camera image and a 3-D world all complicate the task of computer processing of a video image.

Other kinds of sensing devices, from proximity sensors to touch and force sensors, have received much less attention than machine vision, but they also could play an important role in the factory environment, particularly for assembly applications. Sensors will be discussed in greater detail later in the chapter.

Applications. –Table 6 displays some of the most recent robot use estimates. Figure 6 estimates the robot sales and total use in the United States for the next decade. Such statistics should be interpreted with caution, however. In particular, the number of robots in use is a highly imperfect measure of the level of automation and modernization in an industry or country. Process changes in manufacturing which increase productivity may or may not include robots. As one report on international use of robots observes:[9]

> It is also important that robots be viewed as part of the overall changes taking place in manufacturing concepts with the increasing diffusion of automated manufacturing equipment, including computer-aided manufacturing and computer-aided design systems. The impact of new production concepts, equipment and systems on production control and machine utilisation, inventory control and management efficiency will together have a much greater productivity impact than the industrial robot alone.

As noted earlier in this chapter, international comparisons of robot "populations" are also plagued by inconsistencies in the definition of a robot, particularly between the United States and Japan. Regardless of the definition of robot used, Japan leads the world in number of robots in use. The reasons for Japan's emphasis on robot technology include a historical shortage of labor, and a tendency to devote more engineering expertise to manufacturing processes than does the United States. In addition, the United States faced

Table 6.—Operating Robot Installations, End of 1982

Country	Number	Percent of total
Japan	31,900	66
United States	6,301	13
West Germany	4,300	9
Sweden	1,450	3
Italy	1,100	2
France	993	2
United Kingdom	977	2
Belgium	305	t
Poland	285	t
Canada	273	t
Czechoslovakia	154	t
Finland	98	t
Switzerland	73	t
Netherlands	71	t
Denmark	63	t
Austria	50	t
Singapore	25	t
Korea	10	t
Total	48,428	

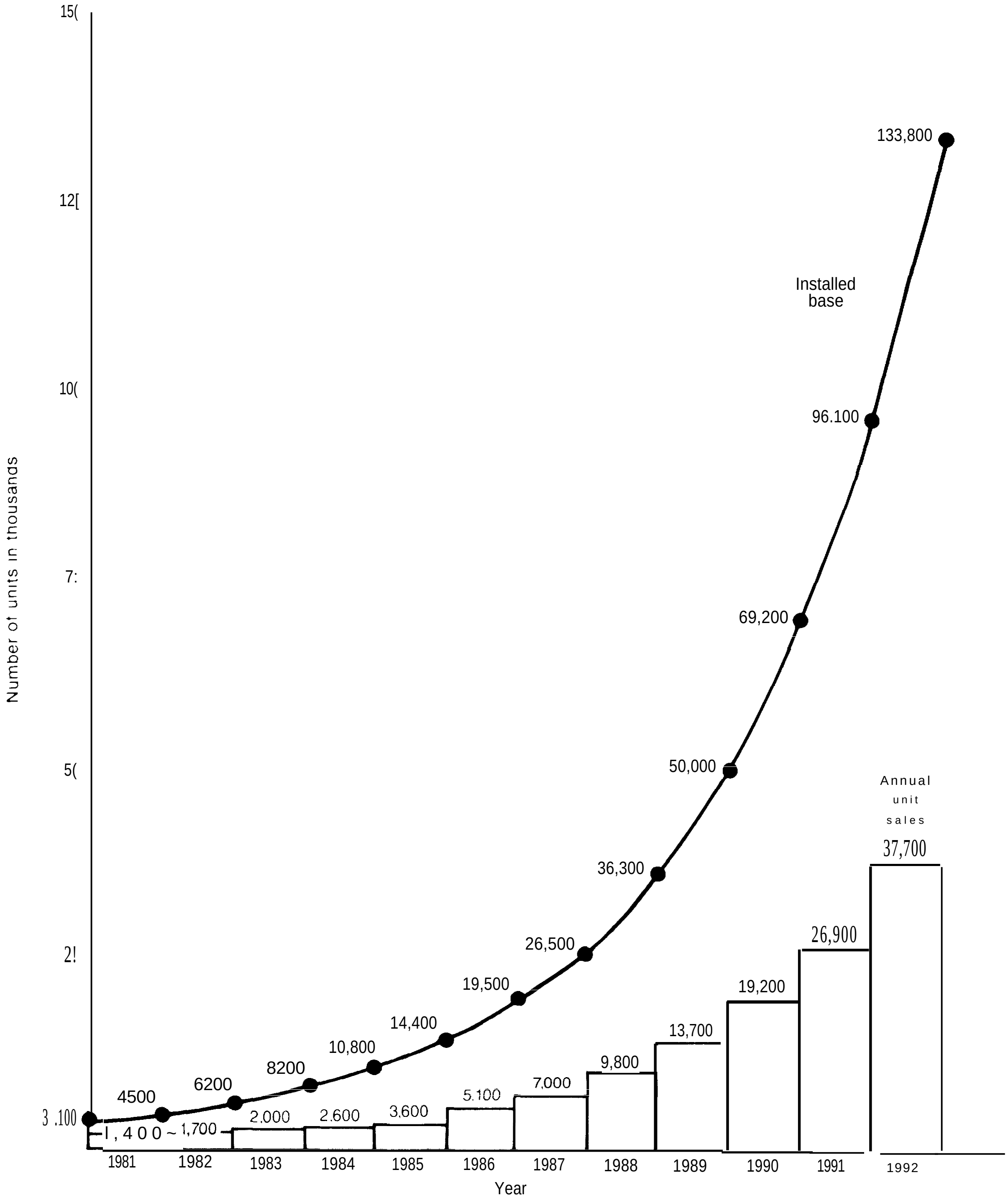
Less than 1 percent.

Note: This table does not include 9,000 "variable sequenced manipulators" which are included in the RIA's estimate for France. Statistics on robots differ because of differing definitions of a robot, because of different methodologies for collecting data, and because "operating robot installations" (as used in this table) may differ from "robot population, " which includes some robots in laboratories and others not yet in use A December 1983 study by the U S. International Trade Commission, for example ("Competitive Position of U S. Producers of Robotics (in Domestic and World Markets") gives slightly different figures for robot population in the United States and West Germany (7 232 and 3,500, respectively)

SOURCE Robot Instutitute of America, *Worldwide Robotics Survey* and D/rectory, 1983

[9]OECD, "Robots: The Users and the Makers, " *The OECD Observer,* July 1983.

Figure 6.—Actual and Projected U.S. Annual Robot Sales and Installed Base Through 1992



NOTE" The projections above are highly speculative. Robot sales have not grown nearly as fast as most Industry observers expected, and one industry analyst suggests that the above figures may be as much as 30 to 50 percent too high (E Lustgarten, Vice President, Paine, Webber, Mitchell, Hutchins, Inc personal communication, Feb 7, 1984) On the other hand, robot vendors and the Robotic Industries Association still believe that a tremendous upsurge in robot sales is forthcoming, and the projections above may even be too low (L Lachowicz, Robotic Industries Association, personal communication Feb 7, 1984) See ch 7 for further discussion of the robot industry and its prospects

SOURCE Tech Traing A Summary and forecast 1983 labor surpluses throughout the 1970's, which tended to induce manufacturers to use labor instead of equipment in production. Chapter 9 will discuss international comparisons in more detail.

Sophistication in reprogramiability, as well as size and degrees of freedom, are some of the key cost factors for an industrial robot. A simple "pick-and-place" machine with 2 or 3 degrees of freedom costs roughly $5,000 to $30,000, while more complex programmable models, often equipped with microcomputers, cost approximately $25,000 to $90,000 and uplo

Table 7 lists some of the potential applications for industrial robots. Many of the first applications of robots have been for particularly unpleasant or dangerous tasks. One of the earliest uses, for example, was for loading and unloading die-casting machines, a hazardous and unpleasant task because of the extreme heat. The best-known uses, however, have been in spray painting and spot welding in the auto and related industries. In these applications, robots have proven to be useful for performing particularly hazardous and monotonous jobs while offering enough flexibility to be easily adapted to changes in car models or body styles.

There are a number of motivations behind the use of robots on such unpleasant jobs. Improvement of job conditions (and, consequently, worker morale) is one of them, though it may not be the primary one. Such jobs often have high worker turnover and inconsistent product quality because of their unpleasantness. Also, compliance with the occupational safety and health regulations that protect people performing these tasks adds to production costs. In addition, tasks like spray painting and spot welding are often relatively easy to automate because the paths the robot is to follow are predictable, and the tasks are repetitive and require little sensing capability.

10 E. Lustgarten, Vice President, paine, Webber, Mitchell! Hutchins, Inc., personal communication.

Table 7.—Examples of Current Robot Applications

Material Handling
- Depalletizing wheel spindles into conveyors
- Transporting explosive devices
- Packaging toaster ovens
- Stacking engine parts
- Transfer of auto parts from machine to overhead conveyor
- Transfer of turbine parts from one conveyor to another
- Loading transmission cases from roller convveyor to monorail
- Transfer of finished auto engines from assembly to hot test
- Processing of thermometers
- Bottle loading
- Transfer of glass from rack to cutting line

Machine loading/unloading:
- Loading auto parts for grinding
- Loading auto components into test machines
- Loading gears onto CNC lathes
- Orienting/loading transmission parts onto transfer machines
- Loading hot form presses
- Loading transmission ring gears onto vertical lathes
- Loading of electron beam welder
- Loading cylinder heads onto transfer machines
- Loading a punch press
- Loading die cast machine

Spray painting:
- Painting of aircraft parts on automated line
- Painting of truck bed
- Painting of underside of agricultural equipment
- Application of prime coat to truck cabs
- Application of thermal material to rockets
- Painting of appliance components

Welding:
- Spot welding of auto bodies
- Welding front-end loader buckets
- Arc welding hinge assemblies on agricultural equipment
- Braze alloying of aircraft seams
- Arc welding of tractor front weight supports
- Arc welding of auto axles

Machining:
- Drilling alum inure panels on aircraft
- Metal flash removal from casings
- Sanding missile wings

Assembly:
- Assembly of aircraft parts (used with auto-rivet equipment)
- Riveting small assemblies
- Drilling and fastening metal panels
- Assembling appliance switches
- Inserting and fastening screws

Other:
- Application of two-part urethane gasket to auto part
- Application of adhesive
- Induction hardening
- Inspecting dimensions on parts
- Inspection of hole diameter and wall thickness

SOURCE" Tech Tran Corp , *Industrial Robots: A Summary and Forecast, 1983*

While spot welding, spray painting, and loading/unloading applications have been the primary uses for robots, increasing sophistication in programmability and in sensing is enabling applications such as arc welding and assembly.

As an example of such an application, a welder at Emhart Corp. 's United Shoe Manufacturing plant in Beverly, Mass., uses a robot to arc-weld frames for shoemaking machinery* (see photo). He welds several dozen identical frame units at a time; each frame unit requires perhaps a dozen 2-inch welds to attach reinforcing bars to a steel sheet. The welder clamps the first sheet and reinforcing bars onto a table. Using directional buttons on a "teach pendant"—a portable panel attached to the robot controller-he directs the robot to the spot where it is to begin the first weld. He pushes a button to record that location. Still using the teach pendant, he moves the robot to the end of the weld and records that location. Then he presses a button which instructs the machine to "weld a straight line from the first point to the second. " After repeating this process for each of the dozen welds, he gives the command for the robot to begin welding, and the robot follows the path it has been "led through "-this time with its welding gun on. For each subsequent identical frame unit, all that is required is to clamp down the parts in the same location as the original set on which the machine was

*OTA sit visit, Emhart Corp., United Shoe Manufacturing Plant, Beverly, Mass., June 28, 1983.

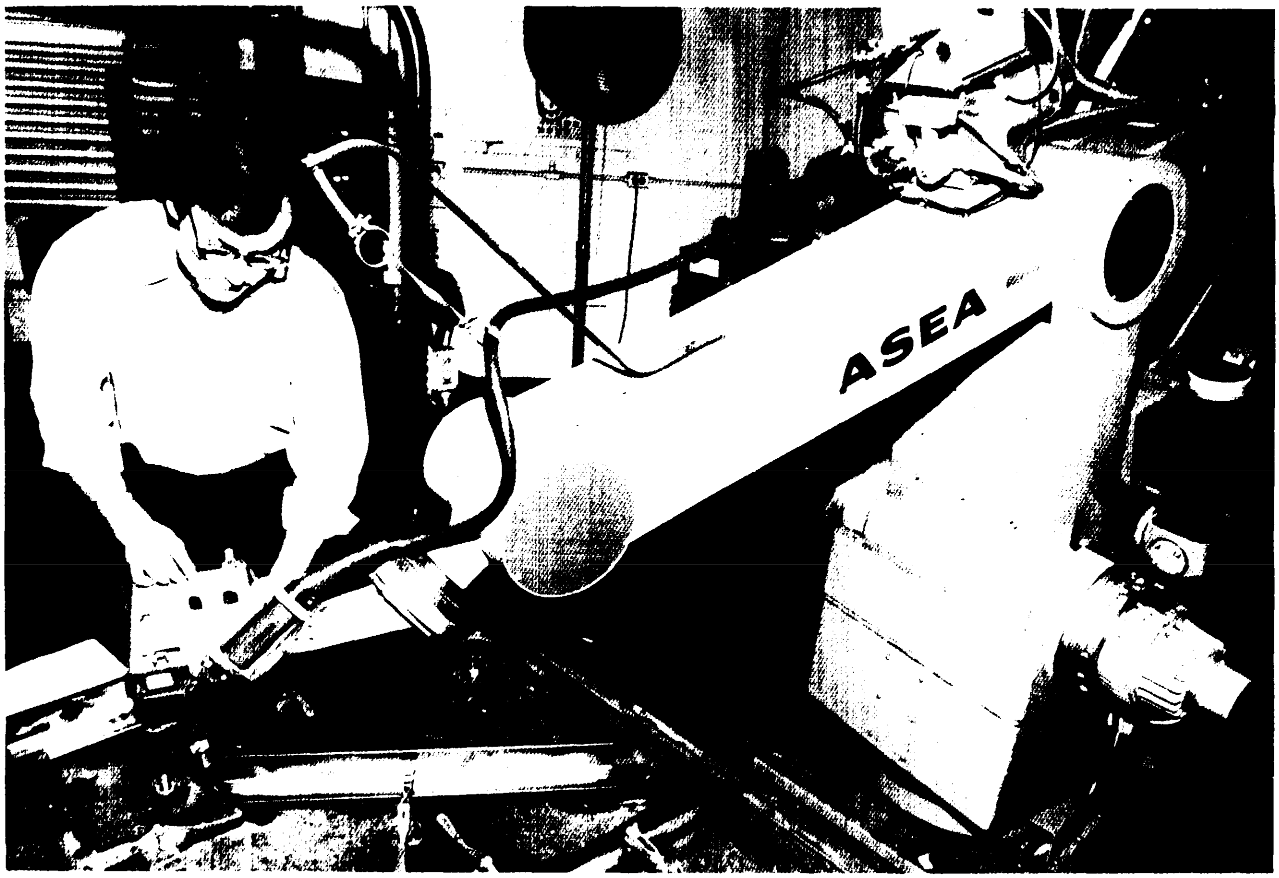


Photo credit Emhart Corp

Welder Pete Bolger at Emhart's United Shoe Manufacturing Plant uses a "teach pendant" to program a robot to weld parts of a metal frame, below left. After the robot is taught the correct steps, it can repeat those steps with its welding gun on, while the operator can set up another frame on an adjacent table or perform other duties

27- 4520-84-5 : OL3

"taught," signal the machine to begin, and then inspect the welds after the machine completes its program. The robot controller can store several programs, so that the operator can use the robot to weld different types of frames in any order he chooses, as long as he sets up the steel plates and reinforcing bars in the appropriate positions.

Note that this application of a robot for arc welding does not use sensors, even though there has been extensive work done on developing vision sensors that allow the robot to "see" the seam formed by the two pieces of metal, and to follow it automatically. For the fairly simple, straight-line applications at Emhart, sensors are not necessary. However, if the frame units were out of position by a half-inch, the welding robot would put a useless blob of metal where it expected the joint to be. If a clamp was in the way of a programed weld, the robot would attempt to weld through the clamp, damaging the clamp and itself in the process.

The advantages of robots depend on whether one is comparing them to hard automation devices or to human workers. Clearly, the flexibility and programiability of robots is prominent in the first case, while in comparison with humans the advantages are likely to be the robot's greater consistency, endurance, and ability to tolerate hostile environments.

The disadvantages of robots also depend on whether they are compared with other automation or humans. In the former case, robotic devices are sometimes more expensive than a hard automation device which is not programmable, and they are not as fast—a typical robot moves about as fast as a human, while dedicated automatic part-transfer devices can operate at considerably greater speed. The clear advantage of human workers over robots, on the other hand, is in situations where extensive sensing, judgment, or intelligence is required, and/or where situations change so frequently that the expense of programing a robot is uneconomical. For these reasons it is often suggested that humans, robots, and hard automation devices are best suited for low, medium, and high production volumes, respectively, although there are many exceptions to this-e. g., automotive spot welding. Each situation must be evaluated individually.

The design of automated production processes involves determining which tasks are most suitable for a machine, and which are most suitable for a human. Several technology experts have argued that some manufacturers' visions of robots as replacements for human workers will prevent the best allocation of tasks between human and machine. One researcher argues:

> A robot is a machine. It should be designed, controlled, and operated as a machine. Any attempt to emulate human behavior with a robot is a misdirection. Take, for example, the task of turning a bolt. A human turns down a bolt in roughly half-revolution increments. At today'state-of-the-art, most robots are constrained to perform the task in the same way. But robots need not be constrained the way humans are. The most distal axis of a robot should be capable of continuous rotation. The primary advantage that robots will have in the manufacturing market of the future will be based not on their ability to mimic humans, but on their abilities to perform tasks in ways which humans cannot.[11]

General-purpose robots are already evolving toward special-purpose programmable devices for a particular task (e.g., assembly machines, painting machines), and this evolution may continue so that few robots in the future look like the general-purpose "arm" of today.

Though they will not be covered in detail here, robotics technology has a wide range of nonmanufacturing uses including handling of radioactive material, mining, undersea exploration, and aids for the handicapped.[12]

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[11] W. P. Seering, "Directions in Robot Design, " *Transactions of the ASME,* March 1983, pp. 12-13.

[12] See, for example, T. N. Sofyanos and T. B. Sheridan, *An Assessment of Undersea Teleoperators,* Sea Grant College Program, Massachusetts Institute of Technology, June, 1980; A. Seireg and J. Grundman, "Design of a Multitask Exoskeletal Walking Device," *Biomechanics of Medical Devices,* D. N. Ghista (cd.) (New York: Marcel Dekker Inc., 1981), pp. 569-639.

Numerically Controlled Machine Tools

Numerically controlled, or NC, machine tools are devices which cut a piece of metal according to programed instructions about the desired dimensions of a part and the steps for the machining process. They consist of a machine tool, specially equipped with motors to guide the cutting process, and a controller which receives numerical control commands.

The U.S. Air Force developed NC technology in the 1940's and 1950's, in large part to help produce complex parts for aircraft which were difficult to make reliably and economically with a manually guided machine tool.

How They Work.—Machine tools for cutting and forming metal are the heart of the metalworking industry. Using a conventional, manual machine tool, a machinist guides the shaping of a metal part by hand. He or she moves either the workpiece or the head of the cutting tool to produce the desired shape of the part. The machinist controls the speed of the cut, the flow of coolant, and all other relevant aspects of the machining process.

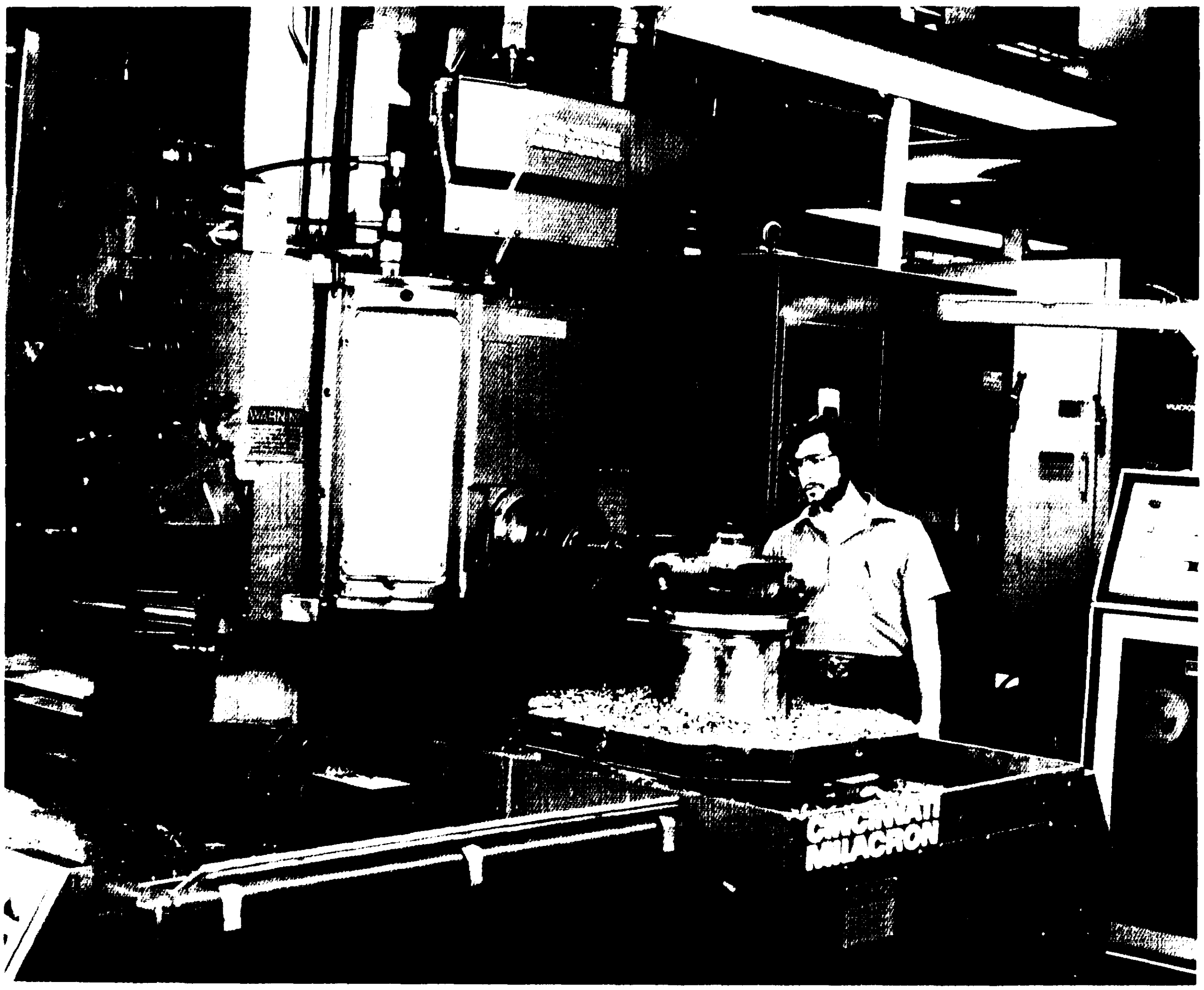


Photo credit Cincinnati Milacron Corp

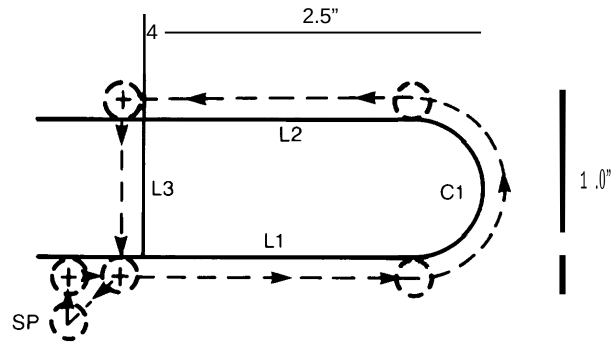
An operator supervises a large, computerized numerically controlled (CNC) machine tool. The minicomputer which controls the tool is at right; at left additional cutting tools are loaded into an automatic tool changing device

In ordinary NC machines, programs are written at a terminal which, in turn, punches holes in a paper or mylar plastic tape. The tape is then fed into the NC controller. Each set of holes represents a command, which is transmitted to the motors guiding the machine tool by relays and other electromechanical switches. Although these machines are not computerized, they are programmable in the sense that the machine can easily be set to making a different part by feeding it a different punched tape; and they are automated in that the machine moves its cutting head, adjusts its coolant, and so forth, without direct human intervention. However, most of these machines still require a human operator, though in some cases there is one operator for two or more NC machine tools. The operator supervises several critical aspects of the machine's operation:

1. he or she has override control to modify the programed speeds (rate of motion of the cutting tool) and feeds (rate of cut) (see fig. 4). These rates will vary depending on the batch of metal used and the condition of the cutting tool;
2. he or she watches the quality and dimensions of the cut, and listens to the tool, replacing worn tools (ideally) before they fail; and
3. he or she monitors the process to avoid accidents or damage-e. g., a tool cutting into a misplaced clamp, or a blocked coolant line.

Typically, NC programs are written in a language called APT (Automatically Programed Tools), which was developed during the initial Air Force research on NC (see fig. 7 for a sample of an APT program). A number of modified versions of APT have been released in the last decade, and some of these are easier to use than the original. But the essential concept and structure of the numerical codes has remained the same. In large part because of the momentum it gained from its initial DOD support, APT has become a de facto standard for NC machine tools.

Figure 7.—Sample APT Computer Program



The path of the center of the cutter is shown as t moves about the perimeter of the part.

```
(1)              PARTNO FLAT PLATE NO 12345678
(2)              MACHIN/MODEL PTX
(3)              CLPRNT
(4)              CUTTER/.25
(5)              FE DRAT/1O
(6)    SP  .     POINT/ -.5, – .5,1
(7)    pl  =     POINT/0,0,0
(8)    L1  =     LINE/PI , ATANGL,O
(9)    cl  =     CIRCLE/2,.5,.5
(lo)   P2  =     PO IN T/0,1 ,0
(11)   L2  =     LINE/P2, PAR LEL, L1
(12)   L3  =     LINE/P2, PERPTO, L1
(13)             FROM/SP
(14)             GO/TO, L1
(15)             GO RGI"/LI ,TANTO,C1
(16)             GOFWD/CI ,TANTO, L2
(17)             GOFWD/L2, PAST, L3
(18)             Go LFT/L3, PAST, L1
(19)             GOTO/SP
(20)             FIN I
```

The APT computer program, above, directs a machine tool to cut around the perimeter of a flat metal part with a semicircular end (see top diagram) In the program, the first line Identifies the part, and line (2) calls out the postprocessor for the machine/control combination that IS to machine the part The postprocessor IS that part of the computer software program that tailors the tape Instruct Ions for the particular machine/control combination Line (3) notes that the computer IS to print out the coordinates of all the straight-llne moves of the cutter Line (4) notes that the cutter is to have a diameter of O 25 Inches. Line (5) describes the feed rate in inches per minute Lines (6) through (12) describe the geometry of the part Lines (13) through (19) are motion statements and describe the path of the cutter Line (20) ends the part program

SOURCE: J. J. Childs, Princlples of Numerical Control (New York: Industrial Press, 1982, pp. 134-135.

Since 1975, machine tool manufacturers have begun to use microprocessors in the controller, and some NC machines come equipped with a dedicated minicomputer. Those called computerized numerically controlled (CNC) tend to be equipped with a screen and keyboard for writing or editing NC programs at the machine. Closely related to CNC is direct numerical control (DNC), in which a larger mini- or mainframe computer is used to program and run more than one NC tool simultaneously. As the price of small computers has declined over the past decade, DNC has evolved both in meaning and concept into distributed numerical control, in which each machine tool has a microcomputer of its own, and the systems are linked to a central controlling computer. One of the advantages of such distributed control is that the machines can often continue working for some time even if the central computer "goes down."

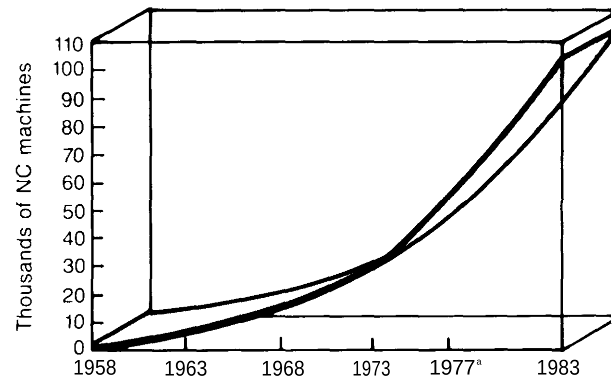
In all types of NC machine tools the machining processes are essentially the same-the difference is in the sophistication and location of the controller. CNC controllers allow the operator to edit the program at the machine, rather than sending a tape back to a programer in a computer room for changes. In addition, by avoiding the use of paper or mylar tape, CNC and DNC machines are substantially more reliable than ordinary NC machines. The tape punchers and readers and the tape itself have been notorious trouble spots. CNC and DNC machines, through their computer screens, may also offer the operator more complete information about the status of the machining process.

Some NC tools are equipped with a feature called "adaptive control," which tries to automatically optimize the rates of cut to produce the part as fast as possible, while avoiding tool failure. As yet, there has been limited success with these devices.

Applications. –The diffusion of NC technology into metalworking industry proceeded very slowly in the 1950's and 1960's, though it has accelerated somewhat over the past 10 years. Figure 8 and table 8 detail the U.S. population of machine tools. Numerically controlled machine tools represent only 4.7 percent of the total population,12 although this figure may be somewhat misleading: the newer, NC machine tools tend to be used more than the older equipment, and firms often keep old equipment even when they buy new machines. Some industry experts have estimated that as many as half of the parts made in machine shops are made using NC equipment. Nevertheless, the applications still tend to be concentrated in large firms and in smaller subcontractors in the aerospace and defense industries.

Two examples from OTA'S case studies illustrate a range of uses for NC machine tools. A Connecticut machine shop with 48 employees on the shop floor began using numerical control technology around 1966, and now uses 23 NC machines to produce contracted parts for the electronics and aircraft industries. By contrast, one of the NC machine shops at a large commercial aerospace manufacturer oc-

Figure 8.—Total Number of Numerically Controlled Machine Tools in U.S. Metalworking



[a] 12th Inventory data collected over 3 years 1976 to 1978

SOURCE 13th American Machinist Inventory *American* Machinist November 1983

Table 8.—Estimated Total Machine Tools in the United States

	Total units	Metal-cutting	Metal-forming
Metalworking	2,192,754	1,702,833	489,921
Other industries	380,000	275,000	105,000
Training , ...	74,000	70,000	4,000
In storage and surplus .	250,000	200,000	50,000
Total	2,896,754	2,247,833	648,921

SOURCE: 13th Annual American Machinist Inventory and estimates, American Machinist, November 1983

[12] "The 13th *American Machinist* Inventory of Metalworking Equipment 1983," *American Machinist,* November 1983, pp. 113-144.

cupies 471,000 square feet—about the size of 18 football fields–and includes 110 NC and CNC machine tools, as well as 230 conventional machine tools.

The U.S. machine tool population is significantly older than that of most other countries (see table 9), and this situation, suggesting relatively low levels of capital investment, has been a source of concern for many in industry and government. In 1983, for the first time in several decades, the percentage of metalcutting tools less than 10 years old increased by 3 percent, although the percentage of metalforming tools less than 10 years old remains at an all-time low of 27 percent.[15]

DOD has encouraged diffusion of NC technology, which has moved beyond the aerospace industry—although not nearly as fast as most observers expected. There are several reasons for the relatively slow diffusion of NC technology. They include high capital cost for an NC machine (perhaps $80,000 to $150,000 and up, as opposed to $10,000 to $30,000 for a conventional machine tool).[16] In addition, the successful application of NC machine tools requires technical expertise that is in short supply in many machine shops. Training is a problem, as some users report requiring as much as 2 years "to get an NC programer up to speed. "[17] Small machine shops typically do not have the resources or expertise to train staff to use or maintain computerized equipment. Finally, "APT proved to be too complicated for most users outside the aerospace industry. . . . Most machine jobs could be specified in a considerably less complex world. "[18]

However, intricate shapes such as those now found in the aerospace industry are nearly impossible for even the most experienced machinist using conventional machine tools. With NC, the parts can be more consistent because the same NC program is used to make the part each time it is produced. A manually guided machine tool is more likely to produce parts with slight variations, because the machinist is likely to use a slightly different procedure each time he or she makes a part. This may not be a problem for one-of-a-kind or custom production, but can cause headaches in batch production. The advantages in consistency due to NC are seen by many manufacturers as an increase in their control over the machining process.

NC machines tend to have a higher "throughput" than conventional machine tools, and hence are more productive. They are operating (i.e., cutting metal) more of the time than a conventional machine tool because all the steps are established before the machining begins and are followed methodically by the machine's controller. Further, on a complex part that takes more than one shift of machining on a conventional machine tool, it is very difficult for a new machinist to take over where the first left off. The part may remain clamped to the machine and the part and machine tool lie idle until the original machinist returns. On NC machines, operators can substitute for each other relatively easily, allowing the machining to continue uninterrupted.

As discussed previously, the capability of guiding machine tools with numeric codes opens up possibilities for streamlining the steps between design and production. The go metric data developed in drawing the product on a CAD system can be used to generate the NC program for manufacturing the product.

Flexible Manufacturing Systems

A flexible manufacturing system (FMS) is a production unit capable of producing a range of discrete products with a minimum of manual intervention. It consists of production equipment workstations (machine tools or other equipment for fabrication, assembly, or treatment) linked by a materials-handling system to move parts from one workstation to

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[14] OTA work environment case studies.

[15] "The 13th *American Machinist* Inventory of Metalworking Equipment 1983, " *American Machinist*, November 1983.

[16] E. Lustgarten, Vice President, Paine, Webber, Mitchell, Hutchins, Inc., personal communication.

17A. M. Greene, "Is It Time for a New Approach to NC Programming?" *Iron Age*, Sept. 24, 1982, p. 83. The need for substantial training applies not only to NC machine tools but to virtually all PA devices.

"Industry and Trade Strategies, unpublished paper prepared for OTA, April 1983, p. 28.

Table 9.—Age of Machine Tools in Seven Industrial Nations

	Year	Metalcutting machines						Metalforming machines					
		Units	O-2 yr	6-4 yr	0-9 yr	>15 yr	>20 yr	Units	o-2 yr	O-4 yr	O-9 yr	>15 yr	>20 yr
United States	83	1,703,000	—	14 %	34 "/0	—	320/o	490,000	—	90/0	180/0	—	37 "/0
Canada	78	149,400	—	—	41	—	37	61,400	—	–	23	–	26
Federal Republic of Germany	80	985,000	–	15	34	480/o	—	265,000	—	15	34	48 '/o	
France	80	584,000	–	16	35	–	32	177,000	—	16	35	–	32
Italy	75	408,300	—	—	41C	—	29'	133,000	—	—	29[c]	—	25'
Japan	81	707,000	150/0	—	35[b]	37[d]	—	211,000	180/0	—	41[b]	31[d]	—
United Kingdom	82	627,900	–	41[a]	—	—	27	146,800	—	48[a]	—	—	28

a 0-5 years old" [b]O-7 years old [c]0.8 years old. '13 years old and up: '18 Years old and UP

SOURCE 13th American Machinist Inventory, *American Machinist*, November 1983 (Note *American Machinist* used a variety of foreign sources for this table) another, and it operates as an integrated system under full programmable control.[19]

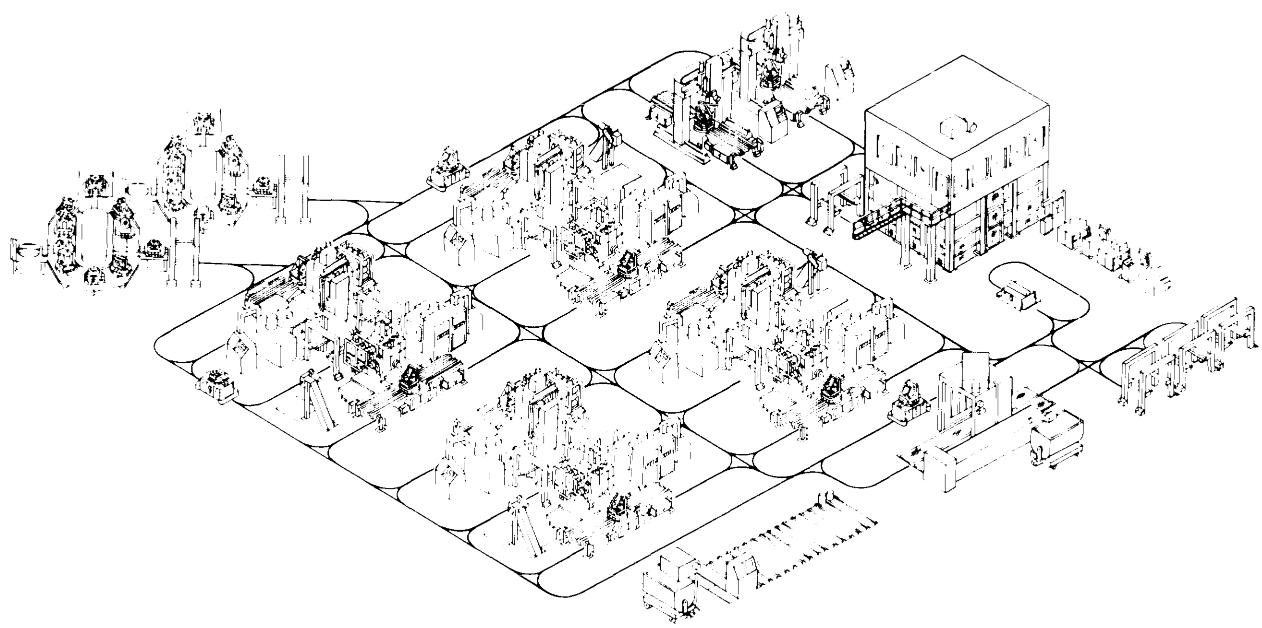
An FMS is often designed to produce a family of related parts, usually in relatively small batches–in many cases less than 100, and even as low as one. Most systems appropriately considered to be an FMS include at least four workstations, and some have up to 32. Smaller systems of two or three machine tools served by a robot, which are sometimes called flexible manufacturing systems, are more appropriately termed "machining cells. "

How an FYWS Works.– Using NC programs and (often) computer-aided process planning, workers develop the process plan (i.e., the sequence of production steps) for each part that the FMS produces. Then, based on inventory, orders, and computer simulations of how the FMS could run most effectively, the FMS managers establish a schedule for the parts that the FMS will produce on a given day. Next, operators feed the material for each part into the system, typically by clamping a block of metal into a special carrier that serves both as a fixture to hold the part in place while it is being machined, and as a pallet for transporting the workpiece. Once loaded, the FMS essentially takes over. Robots, conveyors, or other automated materials handling devices transport the workpiece from workstation to workstation, according to the process plan. If a tool is not working, many FMSS can reroute the part to other tools that can substitute.

Machine tools are not the only workstations in an FMS; other possible stations include washing or heat-treating machines, and automatic inspection devices. While most current FMSS consist of groups of machine tools, other systems anticipated or in operation involve machines for grinding, sheet metal working, plastics handling, and assembly.

The amount of flexibility necessary to deserve the label "flexible" is arguable. Some FMSS can produce only three or four parts of very similar size and shape—e.g., three or four engine blocks for different configurations of engines. One FMS expert argues, however,

[19] M. E. Merchant, personal communication, Oct. 12, 1983. Adapted from a definition developed by the International Institution for Production Engineering Research.



Illusfration credit: Cincinnati Milacron Corp

Schematic diagram of an FMS for producing aircraft parts. The lines indicate paths of automatic devices which bring workplaces to the machines

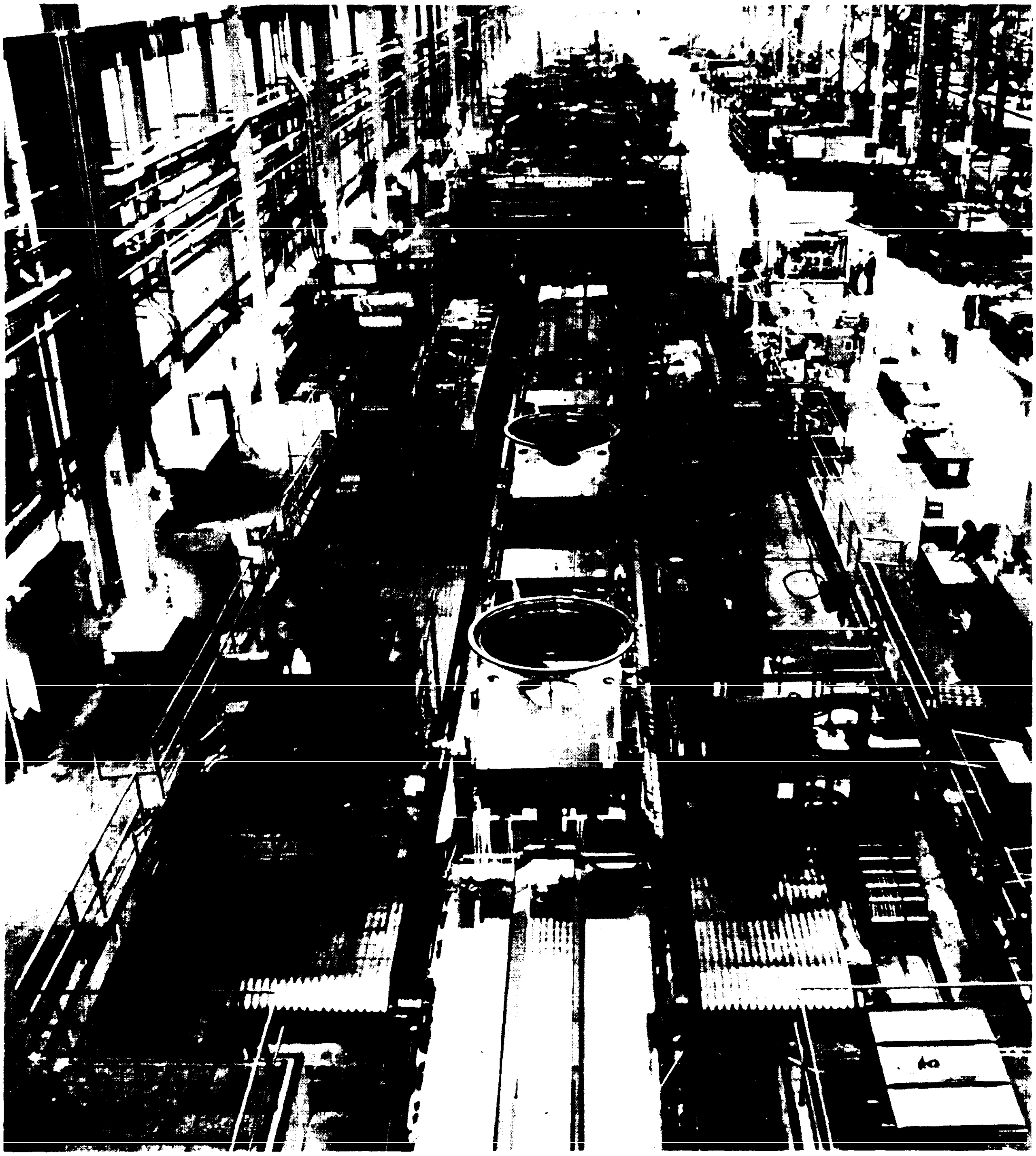


Photo *credit:* Cincinati Corp

An FMS system for tank parts

that in the current state of the technology, a system that cannot produce at least 20 to 25 different parts is not flexible. Indeed, some are being designed to manufacture up to 500 parts.[20]

The essential features that constitute a workable "part family" for an FMS are:

- *A common shape.*—In particular, prismatic (primarily flat surfaces) and rotational parts cannot be produced by the same set of machines.
- Size.–An FMS will be designed to produce parts of a certain maximum size, e.g., a 36-inch cube. Parts larger or much smaller than that size cannot be handled.
- Material. -Titanium and common steel parts cannot be effectively mixed, nor can metal and plastic.
- *Tolerance.* –The level of precision necessary for the set of parts must be in a common range.

Applications. –For a manufacturer with an appropriate part family and volume to use an FMS, the technology offers substantial advantages over stand-alone machine tools. In an ideal FMS arrangement, the company's expensive machine tools are working at near full capacity. Turnaround time for manufacture of a part is reduced dramatically because parts move from one workstation to another quickly and systematically, and computer simulations of the FMS help determine optimal routing paths. Most systems have some redundancy in processing capabilities and thus can automatically reroute parts around a machine tool that is down. Because of these time savings, work-in-process inventory can be drastically reduced. The company can also decrease its inventory of finished parts, since it can rely on the FMS to produce needed parts on demand.

Finally, FMS can reduce the "economic order quantity" for a given part-the batch size necessary to justify setup costs. When a part has been produced once on an FMS, setup costs for later batches are minimal because process plans are already established and stored in memory, and materials handling is automatic. In the ultimate vision of an FMS, the machine could produce a one-part batch almost as cheaply as it could produce 1,000, in cost per unit. In practice there are unavoidable setup costs for apart and a one+part batch is uneconomical. Nevertheless, the FMS's capability to lower the economic order quantity is particularly useful in an economy in which manufacturers perceive an increased demand for product customization and smaller batch sizes. *

A Midwestern agricultural equipment manufacturer, for example, uses an FMS to machine transmission case and clutch housings for a family of tractors (see photo). They had considered "hard automation "-a transfer line–to manufacture the parts, but expected

[20] B Johoski, Manager, Manufacturing Systems Division, Cincinnati Milacron Corp., interview, Aug. 16, 1983.

*In defense production, several examples of the very high Cost of spare parts have come to light. In part because the set up cost for producing parts is so high, the Pentagon's contractors may charge thousands of dollars for producing one or two small parts. The traditional solution to this problem is to make spare parts when the original equipment is bought, and keep the spares on hand. However, studies indicate that more than 95 percent of those spare parts are never used. An FMS could substantially reduce the cost for making a small number of parts because once a part has been made on the system and the tooling and production routing already established, setup costs are relatively low.

Photo credit: Deere & Co,

A worker obtains status information from a computer terminal at one of the workstations of an FMS for producing agricultural equipment a new generation of transmissions within 5 years, which would render the transfer line obsolete. They chose an FMS instead because it could be more easily adapted to other products. In the system, a supervisory computer controls 12 computerized machining centers and a system of chain-driven carts which shuttle the fixtured parts to the appropriate machines. The supervisory computer automatically routes parts to those machines with the shortest queue of workplaces waiting, and can reroute parts to avoid a disabled machine tool. About a dozen employees operate and maintain the system during the day shift, and there are even fewer people on the other two shifts. The system is designed to produce nine part types in almost any sequence desired. (Thus, it is rather inflexible according to the current state of the art.) It was, in fact, one of the earliest FMSS of substantial size to be designed. It was ordered in 1978, but not fully implemented until 1981.[21]

Another example of FMS application is a system operating at Messerschmitt-Bolkow-Blohm's plant in Augsburg, West Germany, to manufacture the center section of Tornado fighter planes at a rate of about 10 per month. The system includes 28 NC machine tools, automatic systems for cutting-tool changing and workpiece transport, and complete computer control. One observer reports:

> The system has demonstrated remarkable efficiencies. They find that the machines in the system are cutting metal, on the average, about 75 percent, or more, of the time—i.e., machine utilization is 75 percent better. Lead time for production of a Tornado is only 18 months, compared to about 30 months for planes produced by more conventional means. The system reduced the number of NC machines required (compared to doing the same job with stand-alone NC machines) by 52,6 percent, required personnel by 52.6 percent, required floor place [sic] by 42 percent, part through-put time by 25 percent, total production time by 52.6 percent, tooling cost by 30 percent, total annual costs by 24 percent and capital investment costs by 10 percent.[22]

Finally, a Fanuc Ltd. factory near Mt. Fuji in Japan has received a great deal of attention and is similarly impressive. The factory produces industrial robots and various CNC tools. It has two automated storage and retrieval systems (these are described in the next section) as well as an automated materials handling system to deliver materials to workstations. Automatic pallet changers and robots are used to load and unload machine teds from the automatic materials handling vehicles, and the plant makes extensive use of unmanned machining at night. The 29 machining centers are attended by 19 workers during the day shift, while at night no one is on the machining floor, and one worker monitors the operation from a control room. Several other areas of this factory are not automated, however—notably, assembly and inspection.[23]

The chief problems related to an FMS arise from its complexity and cost. Several years of planning are needed for such a system, and installing and maintaining an FMS is likely to require a higher degree of technical expertise than manufacturers may have available. Finally, because FMS is a system of interdependent tools, reliability problems tend to magnify. In particular, the materials handling portions of FMS are notoriously troublesome. (See below.)

Despite the advantages claimed for FMS, the systems are still relatively rare. Observers estimate that there are 20 to 30 of such systems in Japan, 20 each in Western and Eastern Europe, and 20 to 30 in the United States.[24] The reasons for this scarcity of application include the complexity, newness and cost of the

[21] 0TA work environment case study.

[22] M. E. Merchant, "Current Status of, and potential for, Au@ mation in the Metalworking Manufacturing Industry, " *Annals of the CIRP*, vol. 32, no. 2, 1983.

[23] Ibid; D. Nitzan, "Robotics in Japan-A Trip Report, " SRI International, February 1982.

[24] "C AM, An International Comparison, *American Machinist*, November, 1981, pp. 207-226; W. Dostal, A. W. Kamp, M. Lahner, and W.P. Seesle, "Flexible Manufacturing Systems and Job Structures" (Mitteilungen aus der arbeitsmarkt and berufsforschung), 1982. Reliable statistics on FMS are difficult to obtain because of conflicting definitions of an FMS and the early stage of the technology's development.

systems. One American manufacturer estimated that FMS cost $600,000 to $800,000 per machining workstation, with a minimum expenditure of $3 million to $4 million.[25] In addition, the in-house costs of planning for installation of an FMS–a process which often takes several years-are likely to substantially increase the investment in an FMS.

Automated Materials Handling Systems

Automated materials handling (AMH) systems store and move products and materials under computer control. Some AMH systems are used primarily to shuttle items to the work areas or between workstations on automated carts or conveyors. Automated storage and retrieval systems (AS/RS) are another form of automated materials handling, essentially comprising an automated warehouse where parts are stored in racks and retrieved on computerized carts and lift trucks. For the purposes of this report, this category includes only those materials handling systems which are not classified as robots.

How AMH Systems Work.–There are a wide variety of formats for automated materials handling. They include conveyors, monorails, tow lines, motorized carts riding on tracks, and automated carriers which follow wires embedded in the floor of the factory. Each AMH system is unique, and each is designed for the materials handling needs of a particular factory. The common characteristic of these devices is that they are controlled by a central computer.

There are three general applications for AMH. The first is to shuttle workplaces between stations on an FMS. In this case, the AMH system operates on commands from the FMS controller. For example, when the controller receives a message that a machine tool has finished work on a certain workpiece, the controller orders the AMH system to pick up the workpiece and deliver it to the next workstation in its routing. The materials handling portion of the FMS is one of its trickiest elements—part transport needs tend to be logistically complicated, and the AMH system must place the part accurately and reliably for machining. Many AMH systems, such as conveyors or tow chains, are serial in nature—i.e., there is only one path from Point A to Point B. This has caused FMSS to cease operating when a cart becomes stuck or a critical path becomes unusable. FMS designers have responded to this problem by designing AMH systems with backup paths, or by using systems such as the wire-guided vehicle mentioned earlier, which can be routed around disabled carts or other obstacles.

Photo credit' Cincinnati Milacron Corp

Automated guided vehicle (also known as a "robot cart") follows wires embedded in the floor of the factory in order to shuttle workplaces from one part of the plant to another

The second major application of AMH is for transporting work-in-process from one manufacturing stage to the next within a factory. This application is similar in concept to AMH use for a flexible manufacturing system, although serving an entire factory is more complex. There is more area to cover, more potential obstacles and logistical difficulties in

[25] B. Johoski, Manager, Manufacturing Systems Division, Cincinnati Milacron Corp., interview, Aug. 16, 1983.

establishing paths for the AMH carriers, and a wider range of materials to handle. For this reason, whole-factory AMH systems are not yet widely used. However, General Motors has recently agreed to purchase automatic guided vehicles from Volvo which allow automobiles to proceed independently through the plant while being assembled. The "robot carts" can be programed to stop at appropriate workstations, and the cart system essentially replaces an assembly line. Volvo uses about 2,000 of the carts in its own plants in Europe.[26] Fiat also uses such carts in Italy.

The final application for AMH is in automated storage and retrieval systems. These systems are often very tall in order to conserve space and to limit the number of automatic carrier devices needed to service the facility. In many cases the structure housing the AS/RS is built separately adjacent to the main factory building. Design of an AS/RS depends on the size of the products stored, the volume of material to be stored, and the speed and frequency of items moving in and out of the system. Advocates of AS/RS cite advantages for the system, as compared to nonautomated systems, which include lowered land needs, fewer (but more highly trained) staff, more accurate inventory records, and lower energy use.

26+. Walter, "Volvo Will Build Robot Carts, " *The Detroit News*, Sept. 27, 1983.

Photo credit Cincinnati Milacron Corp

An automated storage and retrieval system (AS/RS), with a computer terminal showing its status. An "automatic stacker crane" (top, center) operates under computer control

Applications. –In theory, AMH systems can move material quickly, efficiently, and reliably, and keep better track of the location and quantities of the parts by use of the computer's memory, thus avoiding much paperwork. They can minimize loss of parts in a factory, which is a common problem in materials handling.

Deere & Co., for example, uses an extensive AS/RS to store materials and inventory at one of its tractor plants.[27] The system's computerized controller keeps track of the products stored on the shelves, and workers can order the system to retrieve parts from the shelves by typing commands at a computer terminal. After they are retrieved from the AS/RS, the parts can be automatically carried by overhead conveyors to the desired location within the plant complex.

IBM's Poughkeepsie plant is planning an AMH conveyor cart system for transporting a 65-pound computer subassembly fixture between assembly and testing stations. The manufacturing manager reports that the decision to adopt this system was prompted by logistical difficulties in keeping track of many such fixtures among a great variety of workstations, as well as by worker health problems related to transporting the fixtures manually. *

AMH systems often have reliability problems in practice. A Deere & Co. executive related an anecdote at a recent National Re-

[27]G. H. Millar, vice president, Engineering, Deere & Co., address to National Research Council seminar on "The Future of Manufacturing in the United States, " Washington, D. C., Apr. 13, 1983.

*OTA site visit, IBM Corp., Poughkeepsie, NY, June 9, 1983.

search Council symposium.[28] Deere's AS/RS was systematically reporting that they had more engines stored on the racks than other records indicated. After long weeks of searching for the problem they finally found the culprit: A leak in the roof was allowing water to drip past the photocell that counted the engines as they were stored. In essence each drip became an engine in the computer's inventory.

Although Deere's experience is doubtless not widely applicable to AS/RSs, the notion that AMH systems seem to present unexpected logistical and mechanical problems does seem to be generally accurate. Even though these systems are a key aspect of flexible manufacturing systems and of computer-integrated manufacturing, materials handling has long been a neglected topic in industrial research. Materials handling system manufacturers have only recently "caught up" to other industrial systems in level of sophistication, and few companies have so far installed sophisticated AMH systems. Because of this relative lack of sophistication, materials handling for FMS and CIM, especially for a complex application such as delivery of multiple parts to an assembly station, may be one of the biggest problems facing integrated automation.[29]

Other CAM Equipment

While they will not be addressed in detail, there are several other kinds of programmable automation equipment used in manufacturing. They include:

- *Computer-aided inspection and test equipment.* — For mechanical parts, the most prominent such device is the Coordinate Measuring Machine, which is a programmable device capable of automatic and precise measurements of parts. A great variety of inspection and test equipment is also used for electronic parts. IBM's Poughkeepsie plant, mentioned above, performs the vast majority of its testing of microprocessor modules with automatic devices built in-house. In addition, robots can be used as computer-aided inspection and test devices; several two-armed, gantry-style robots are used at IBM to test the wiring for computer circuit boards.* In the test, thousands of pairs of pins on the circuit board must be tested to make sure that they are correctly wired together. Each arm of the robot is equipped with an electronic needle-like probe, and by touching its probes to each

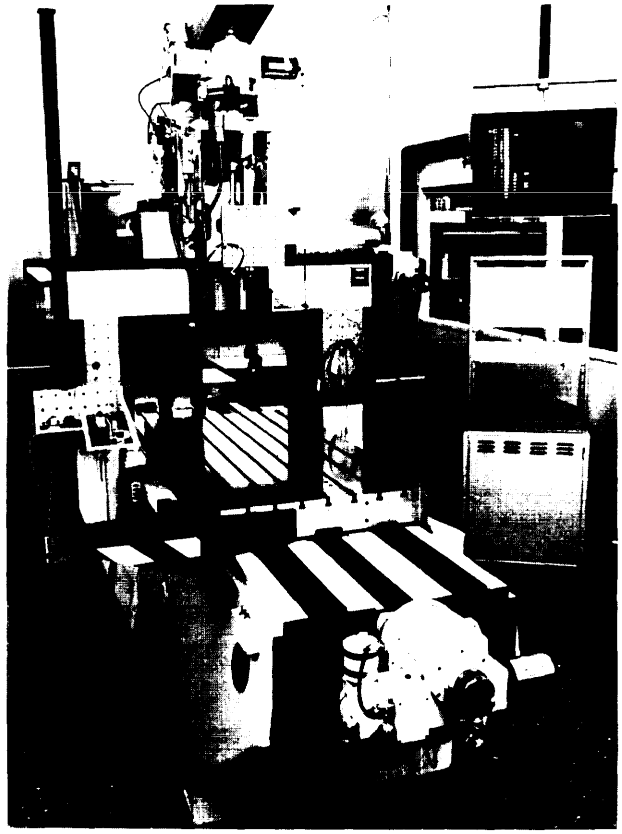


Photo credit National Bureau of Standards

A Coordinate Measuring Machine uses a tiny but precise probe (center) to automatically measure parts

28G. Milk, op. cit.

[29]B. Roth, professor of mechanical engineering, Stanford University, "Principles of Automation, " address to the Unilever Symposium on Future Directions in Manufacturing Technology, Apr. 6-7, 1983; and J. Apple, senior vice president, Systecon, Inc., "Retrieval and Distribution Systems-A Pivotal Part of Future Process Planning, " address to Technology Transfer Society Symposium on Factory of the Future, Oct. 26-28, 1983.

OTA site visit, IBM Corp., Poughkeepsie, N. Y., June 9 1983.

pair of pins and passing an electronic signal through the probes, the robot's control computer can determine whether the circuit board's wiring is "OK."

- *Electronics assembly.* —Increasingly, programmable equipment is used to insert components— resistors, capacitors, diodes, etc.—into printed circuit boards. One such system, Dyna-Pert, manufactured by a subsidiary of the Emhart Corp., is capable of inserting 15,000 parts per hour. A programmable machine assembles spools of electronic parts in the right order for insertion into the circuit board, and another machine inserts the components.
- *Process control.* –Programmable controllers (PCs) are being used extensively in both continuous-process and discrete-manufacturing industries. PCs are small, dedicated computers which are used to control a variety of production processes. They are useful when a set of electronic or mechanical devices must be controlled in a particular logical sequence, as in a transfer line where the conveyor belt must be sequenced with other tools, or in heat treatment of metals in which the sequence of steps and temperature must be controlled very precisely. Until the late 1960's, PCs were comprised of mechanical relays, and were "hard-wired' '–one had to physically rewire the device to change its function or order of processes. Modern PCs are computerized, and can typically be reprogrammed by plugging a portable computer terminal into the PC. A computerized PC is not only more easily reprogrammed than a hard-wired device, but is also capable of a wider range of functions. Modern PCs, for example, are often used not only to control production processes but also to collect information about the process. PCs and numerical control devices for machine tools are very similar in concept—essentially, NCS are a specialized form of PC designed for controlling a machine tool.

Programmable Automation and Manufacturing Management

Several kinds of computerized tools are becoming available to assist in management and control of a manufacturing operation. The essential common characteristic of computerized tools for management is their ability to manipulate and coordinate "data bases"-stores of accumulated information about each component of the manufacturing process. The ability to quickly and effectively get access to these data bases is an extraordinarily powerful management tool–what was a chaotic and murky manufacturing process can become much more organized, and its strengths and weaknesses more apparent. The following section describes some of these tools, as well as the notion of "computer-integrated manufacturing, " which is not a tool or technology in itself but rather a strategy for organizing and controlling the factory.

Management Information Systems

Manufacturers use and store information on designs, inventory, outstanding orders, capabilities of different machines, personnel, and costs of raw materials, among other things. In even a modestly complex business operation, these data bases become so large and intricate that complex computer programs must be used to sort the data and summarize it efficiently. Management information systems (MIS) perform this function, providing reports on such topics as current status of production, inventory and demand levels, and personnel and financial information.

Before the advent of powerful computers and management information systems, some of the information which MIS now handle was simply not collected. In other cases, the collection and digestion of the information required dozens of clerks. Beyond saving labor, however, MIS bring more flexible and more widespread access to corporate information. For example, with just a few seconds of computer time a firm's sales records can be listed by region for the sales staff, by dollar amount for the sales managers, and by product type for production staff. Perhaps most importantly, the goal for MIS is that the system should be so easy to use that it can be used directly by top-level managers.*

Computer-Aided Planning

Computer-aided planning systems sort the data bases for inventory, orders, and staff, and help factory management schedule the flow of work in the most efficient manner. Manufacturing resources planning (MRP) is perhaps the best-known example of computer-aided planning tools.** MRP can be used not only to tie together and summarize the various data bases in the factory, but also to juggle orders, inventory, and work schedules, and to optimize decisions in running the factory. In some cases these systems include simulations of the factory floor so as to predict the effect of different scheduling decisions. MRP systems have applicability for many types of industry in addition to metalworking.

Another kind of computer-aided planning tool is computer-aided process planning (CAPP), used by production planners to establish the optimal sequence of production operations for a product. There are two primary types of CAPP systems—variant and generative.

The variant type, which represents the vast majority of such systems currently in use, relies heavily on group technology (GT). In GT, a manufacturer classifies parts produced according to various characteristics: e.g., shape, size, material, presence of teeth or holes, and tolerances. In the most elaborate GT systems, each part may have a 30- to 40-digit code. GT makes it easier to systematically exploit similarities in the nature of parts produced and in machining processes to produce them. The theory is that similar parts are manufactured in similar ways. So, for example, a process planner might define a part, using GT classification techniques, as circular with interior holes, 6'' diameter, 0.01'' tolerance, and so forth. Then, using a group technology-based CAPP system, the planner could recall from computer memory the process plan for a part with a similar GT classification, and edit that plan for the new, but similar, part.

Generative process planning systems, on the other hand, attempt to generate an ideal routing for a part based on information about the part and sophisticated rules about how such parts should be handled, and the capabilities of machines in the plant. The advantage of such systems is that process plans in variant systems may not be optimal. A variant system uses as its foundations the best guesses of an engineer about how to produce certain parts. The variants on that process plan may simply be variations on one engineer's bad judgment.

Though generative CAPP may also depend on group technology principles, it approaches process planning more systematically. The principle behind such systems is that the accumulated expertise of the firm's best process planners is painstakingly recorded and stored in the computer's memory. Lockheed-Georgia, for example, developed a generative CAPP system called Genplan to create process plans for aircraft parts (see photo for an example of a process plan developed by Genplan). Engineers assign each part a code based on its geometry, physical properties, aircraft model, and other related information. Planners can then use Genplan to develop the routing for the part, the estimated production times, and the necessary tooling. Lockheed-Georgia officials report that one planner can now do work that previously required four to eight people, and that a planner can be trained in 1 year instead of 3 to 4.*

*Sometimes the terms "management information system" and "data base management system" (DBMS) are used interchangeably. MIS tends to refer to a more powerful and comprehensive DBMS aimed for use by relatively high-level staff.

**TWO forms of MRP are mentioned in industry literature. The earlier version was materials requirements planning, a more limited form of computer-aided planning system for ordering and managing inventory. Manufacturing resources planning is sometimes known as MRP II to distinguish it from this earlier notion.

*OTA site visit, Lockheed-Georgia, Mar. 10-11, 1983. Genplan was derived from a generative CAPP system developed by Computer Aided Manufacturing-International-a consortium for programmable automation research (see ch. 8).

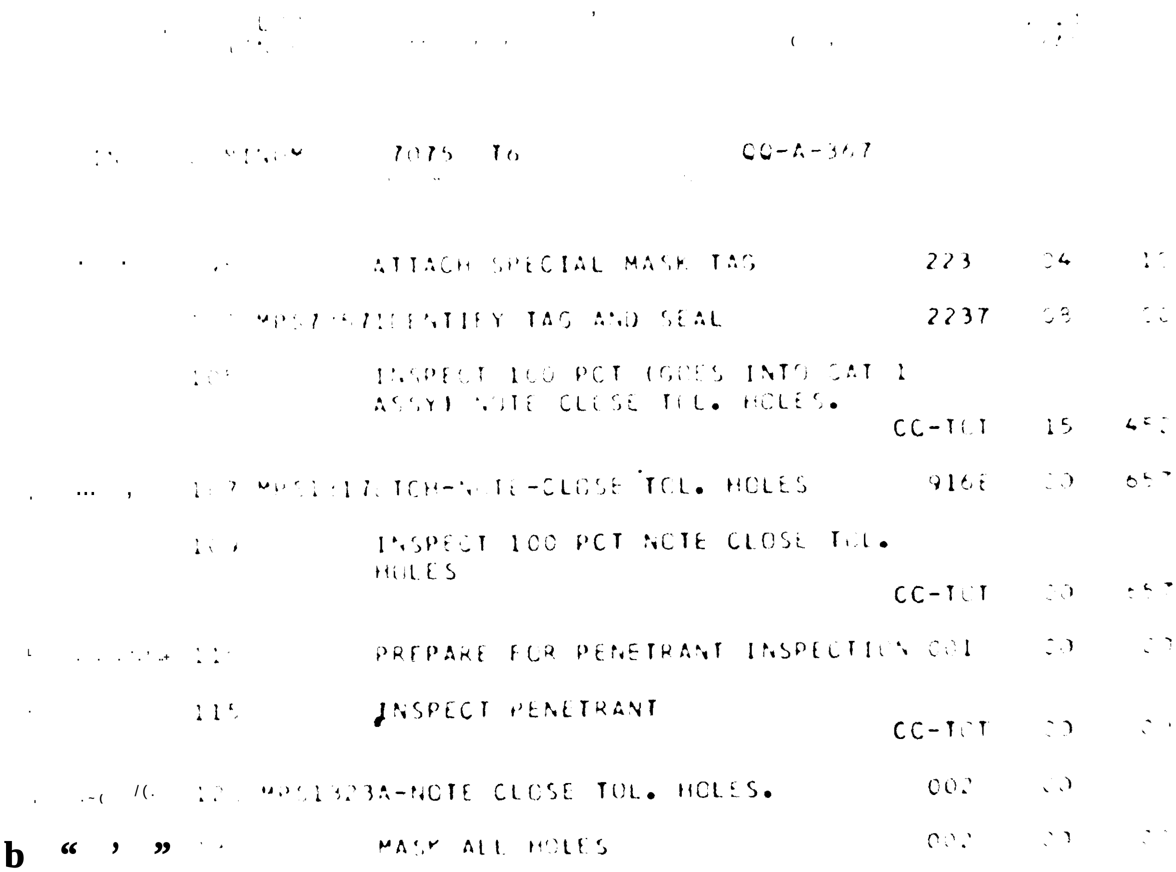


Photo credit Lockheed. Georgia Corp

An excerpt from a process plan developed by the "Genplan" system

Computer-Integrated Manufacturing

Computer-integrated manufacturing (CIM, pronounced "sire") involves the integration and coordination of design, manufacturing, and management using computer-based systems. Computer-integrated manufacturing is not yet a specific technology that can be purchased, but rather an approach to factory organization and management.

Computer-integrated manufacturing was first popularized by Joseph Harrington's book of the same name, published in 1974. One systems expert recounts the history of the concept *in* this way:

> ICIM] came about from: 1) The realization that in many cases automation for discrete activities in manufacturing, such as design or machining, in fact often decreased the effectiveness of the entire operation–e.g., designers could conceive parts with CAD that could not be made in the factory; NC machine tools required such elaborate setup that they could not be economically programmed or used. 2) Development of large mainframe computers supported by data base management systems (DBMS) and communications capabilities with other computers. The DBMS and communications allowed functional areas to share information with one another on demand. 3) The dawning of the microcomputer age which began to allow machines in the factory to be remotely programmed, to talk to each other and to report their activity to their ultimate source of instruction.[30]

[30] D. Wisnosky, group vice president, GCA Corp., Industrial Systems Group, personal communication, October 1983. Wisnosky is a former director of the U.S. Air Force Integrated Computer-Aided Manufacturing Program (ICAM).

Though there is no quantitative measure of integration in a factory, and definitions of CIM vary widely, the concept has become a lightning rod for technologists and industrialists seeking to increase productivity and exploit the computer in manufacturing. For example, James Lardner, vice president of Deere & Co., sees the current state-of-the-art manufacturing process as a series of "islands of automation, " in which machines perform tasks essentially automatically, connected by "human bridges. " The ultimate step, he argues, is to connect those islands into an integrated whole through CIM and artificial intelligence (described in the next section of this chapter), replacing the human bridges with machines. In this essentially "unmanned factory, " humans would then perform only the tasks that require creativity, primarily those of conceptual design. Lardner's vision is echoed by many other prominent experts.

Experts differ in their assessment of how long it might take to achieve this vision—virtually no one believes that it is attainable in less than 10 to 15 years, while some experts would say an unmanned factory is at least three decades away. More importantly, there are other technologists who argue that the vision may, in fact, be just a dream. For example, Bernard Roth, professor of mechanical engineering at Stanford University, argues that factories will, in reality, reach an appropriate and economical level of automation and then the trend toward automation will level off. In a sense, the difference between these two views may be a difference of degree rather than kind. For many factories, the "appropriate" level of automation might indeed be very high. In others, however, a fair number of humans will remain, though they may be significantly fewer than is currently the case.

Integrated systems are often found to require more human input than was expected.[31] Indeed, as one engineer explains:[32]

> There is much talk about the totally automated factory—the factory of the future—and night shifts where robots operate the factory. Whereas these situations will develop in some cases . . . many manufacturing facilities will not be fully automated. Even those that are will involve humans in system design, control, and maintenance—and the factory will operate within a corporate organization of managers and planners.

These two views do have important significance for how an industrialist might now proceed. Many who hold the vision of the unmanned factory seem to emphasize technologies, such as robotics, that can remove humans from manufacturing. Those who do not share the vision of "unmanned manufacturing' tend to argue that there are more practical ways to enhance productivity in manufacturing, including redesigning products for ease of fabrication and assembly.

How *CIM* Works.—There are two different schemes for CIM: In vertically integrated manufacturing, a designer would design a product using a CAD system, which would then translate the design into instructions for production on CAM equipment. Management information systems and computer-aided planning systems would be used to control and monitor the process. A horizontal approach to integration, on the other hand, would attempt to coordinate only the manufacturing portion of the process; i.e., a set of computer-aided manufacturing equipment on the factory floor is tied together and coordinated by computer instructions. A flexible manufacturing system would be a good example of such horizontal integration. * Vertically integrated manufacturing is what is most commonly meant by CIM, however, and many experts would consider horizontal or "shop floor" integration to be only partial CIM. Figure 9 is a conceptual framework for CIM which illustrates the role of some of the PA technologies at various levels of factory control.

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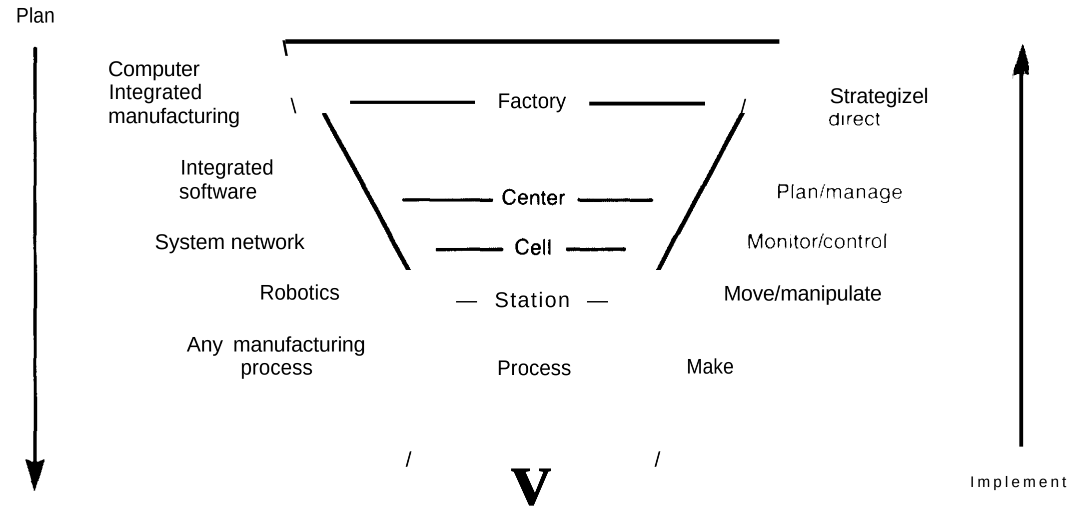
[31] This phenomenon has been noted in a variety of places, including OTA work environment case studies, and the OTA Automation Technology Workshop, May 29, 1983.

[32] B, Bums, Manufacturing Technology Group Engineer, Lockheed-Georgia Co., cited in "Considering People Before Implementation, " *CAD/CAM Technology,* fall 1983, p. 6.

*Vertical and horizontal integration of programmable automation equipment should not be confused with vertical and horizontal integration in the markets for selling this equipment; this will be discussed in chapter 7.

Figure 9.— Programmable Automation Factory Hierarchy (Simplified)



SOURC GCA Corp Industrial Systems Group

A vertically integrated factory usually implies maximum use and coordination of all PA technologies, and can involve much more centralized control of manufacturing processes than a nonintegrated production process. Communication and shared data bases are especially important for CIM. For example, CAD systems must be able to access data from inventory on the cost of raw materials, and from CAM systems on how to adapt the design to facilitate manufacture. Computer-aided manufacturing systems must be able to interpret the CAD design and establish efficient process plans. And management computer tools should be able to derive up-to-date summary and performance information from both CAD and CAM data bases, and effective ly help manage the manufacturing operation.

Some parts of the above requirements are already possible, while others seem far on the horizon. Factory data bases now tend to be completely separate, with very different structures to serve different needs. In particular, the extensive communications between CAD and CAM data bases will require more sophistication in both CAD and CAM, research on how to establish such communications, and finally, major changes in traditional factory data structures in order to implement such a system.

Ap@'cations. -CIM sounds like utopia to many manufacturers because it promises to solve nearly all of the problems in manufacturing that were identified in the section on "the manufacturing process" at the beginning of this chapter, and in particukir it promises to dramatically increase managerial control over the factory. Design changes are easy with extensive use of CAD; CAP and MIS systems help in scheduling; FMS and other CAM equipment cut turnaround time for manufacture, minimize production costs, and greatly increase equipment utilization; connections from CAD to CAM help create designs that are economical to manufacture; control and communication is excellent, with minimal paper flow; and CAM equipment minimizes time loss due to setup and materials handling.

@Many of the companies which make extensive use of computers view their factories as examples of CIM, but on close examination their integration is horizontal-in the manufacturing area only–or at best includes primarily manufacturing and management. Boeing, however, has made substantial strides toward a common design and manufacturing data base system in their CAD/CAM Integrated Information Network (CIIN). Similarly, General Electric, as part of its effort to become a major vendor of factory automation systems, has embarked on ambitious plans for integration at several of its factories, including ity Erie Locomotive Plant, its Schenectady Steam Turbine Plant, and its Charlottesville Controls Manufacturing Division.

Technical Trends and Barriers: Future Applications

While the possibilities for application of existing programmable automation tools are extensive, the technologies continue to develop rapidly. They depend on and share the extraordinary rate of growth in technical capabilities of computer technologies as a whole.

There are five themes in the directions for development in each of the technologies. They are:

- increasing the power of the technologies—i.e., their speed, accuracy, reliability, and efficiency;
- increasing their versatility—the range of problems to which the technologies can be applied;
- increasing the ease of use, so that they require less operator time and training, can perform more complex operations, and can be adapted to new applications more quickly;
- increasing what is commonly called the intelligence of the systems, so that they can offer advice to the operator and respond to complex situations in the manufacturing environment; and
- increasing the ease of integration of PA devices so that they can be comprehensively coordinated and their data bases intimately linked.

This section first summarizes the principal research efforts and directions for development of the five technologies on which this report primarily focuses: CAD, robotics, NC machine tools, FMS, and CIM. Next, it summarizes issues in several technical areas which have a large potential impact on all the technologies: artificial intelligence, standards and interfaces, human factors, materials, and sensors. Chapters 8 and 9 describe the institutional context for research and development (e.g., sources of R&D funding), and compare R&D programs on an international basis.

Trends and Barriers in Five Technologies

Computer-Aided Design

There are at least three generations of CAD equipment, two of which are widely available commercially, with the third still largely in prototype applications and R&D labs. The first are the 2-D computerized drafting systems mentioned earlier in the chapter, which streamline the process of drawing and, especially, editing the drawings of parts, plans, or blueprints. The second generation are 3-D CAD systems, which allow the user to draw an image of a part using either wireframe models or "surfacing" (displaying the surfaces of objects).

The third generation, commercially available within the past few years but still in their infancy me the so-called solid modelers. Such systems (actually an expanded 3-D capability) can be used not only to draw the object in three dimensions but also to obtain a realistic visualization of the part. Users can rotate, move and view the part from any angle, and, in some cases, derive performance characteristics. Engineers at IBM's Poughkeepsie plant, for example, use an advanced CAD system of this type to design cabinet arrangements for IBM mainframe computers. Because the system "constructs" a sophisticated solid model of an object, it can be used to visualize such design issues as component clearance problems. One can even "pull out a drawer" to make sure it does not hit a cable, for instance.

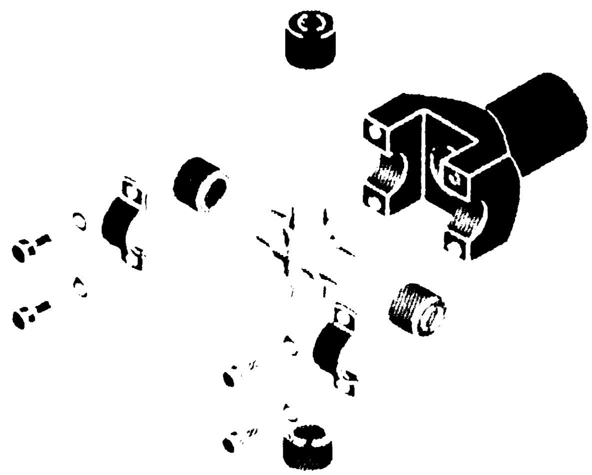


Photo credit Coputervision Corp

An exploded view of a part assembly from a CAD system with solid modeling capabilities

There seems to be a consensus among manufacturing managers and researchers that such third-generation 3-D CAD systems are a critical element in the progress toward effective and powerful use of programmable automation in factories. The increased sophistication of 3-D systems greatly improves the ability of such systems to communicate design specifications to manufacturing equipment. While third generation 3-D systems are technically feasible now, there are nontechnical barriers to implementation of 3-D systems, in part because of the complexity of the systems and the problems encountered in switching from 2-D to 3-D systems.[33] In fact, there is a need for a fourth generation, a CAD system which offers more "intelligent" design assistance and can be easily linked to other programmable automation systems for manufacturing and management.

Indeed, there seem to be three related themes in current CAD research:

1. improving the algorithms for representing objects using the computer so designers can create and manipulate complex objects in an efficient and intuitively clear fashion;
2. adding "intelligence' to CAD systems so that they prevent design errors and facilitate the design process; and
3. developing effective interfaces between CAD systems and manufacturing and management.

Improving Algorithms. –Representing shapes in computer memory and manipulating those representations has been and remains a difficult challenge for computer researchers. As the power and complexity of CAD systems increase, their computing needs grow rapidly. One of the problems in manipulating complex shapes with the computer is illustrated by the experimental CAD system used for computer cabinet design at IBM: One of its creators reported that a typical manipulation of a complex object—say, generating an image of the cabinet from a different viewing angle, with all hidden lines removed—might take several minutes of computer processing time. * Although the system is still useful, clearly quicker response is needed for the designer to have optimal flexibility from a CAD system. A shorter response time can come from a faster computer or from more efficient ways of representing and manipulating shapes in computer memory.

Although faster computers are unquestionably on the horizon, much of the current research on CAD involves attempts at more efficient representations. The efficiency of a certain scheme also depends on how easy it is to use. A wide variety of schemes are being studied, none of which has a clear overall superiority. One scheme, called "constructive solid geometry, " involves assembling images by combining simple shapes, such as blocks, cylinders, and spheres. The other is boundary representation, in which an object is con-

"R. Simon, Computervision Corp., personal communication. Oct. 6, 1983.

*OTA Site visit, D. Grossman, IBM Corp. Yorktown Heights, N. Y., June 8, 1983. "Hidden lines" in images are those edges of a solid object that one cannot see from a given viewing angle. Grossman reports that when CAD is used for such mechanical models as the computer cabinets discussed here, each model consists of a polyhedron with roughly 40,000 separate faces for the computer to store, manipulate, and determine whether they would be "hidden' or not.

structed as a set of individual surfaces. For example, one system being developed by a group at the University of Utah is based on "splines." The designer manipulates on the screen the equivalent of the thin metal strips used in models of boats or planes. He or she can expand them, curve them, cut them, and so forth to create the model.[34]

There is some concern that not enough time and effort in industry is being devoted to expanding the technologies, particularly the algorithms available for "solids modeling, " i.e., for true three-dimensional representations of objects. Thus the "experience base" of industries experimenting with 3-D systems is very small, and such experience is necessary to refine the systems and determine the needs of manufacturing industries.

Adding "Intelligence" to CAD.–In the industry there is much discussion of "smart" CAD systems which would not permit certain operator errors. For example, they would not permit the design of an object that could not be manufactured, a case without a handle, or a faulty circuit board. Further, they would facilitate the designer's work by such functions as comparing a design to existing designs for similar objects, and storing data on standard dimensions and design sub-units, such as fastener sizes and standard shapes. Such systems might also increase the ability of CAD systems to simulate the performance of products. There is much concern over "bad design" in industry, and intelligent CAD systems are considered one way to improve the situation.

Though such systems have become rather advanced in electronics applications and offer some hope of becoming more so, there is as yet little in the way of "smart" CAD systems for mechanical applications. A few systems can be programed to question a designer's choice of certain features that are nonstandard-a 22-mm screw hole in a shop that only uses 20- and 30-mm holes, for instance. Some researchers feel that it will be possible to use an "expert" system (see the next section's discussion of artificial intelligence) for developing a "smart" CAD system.

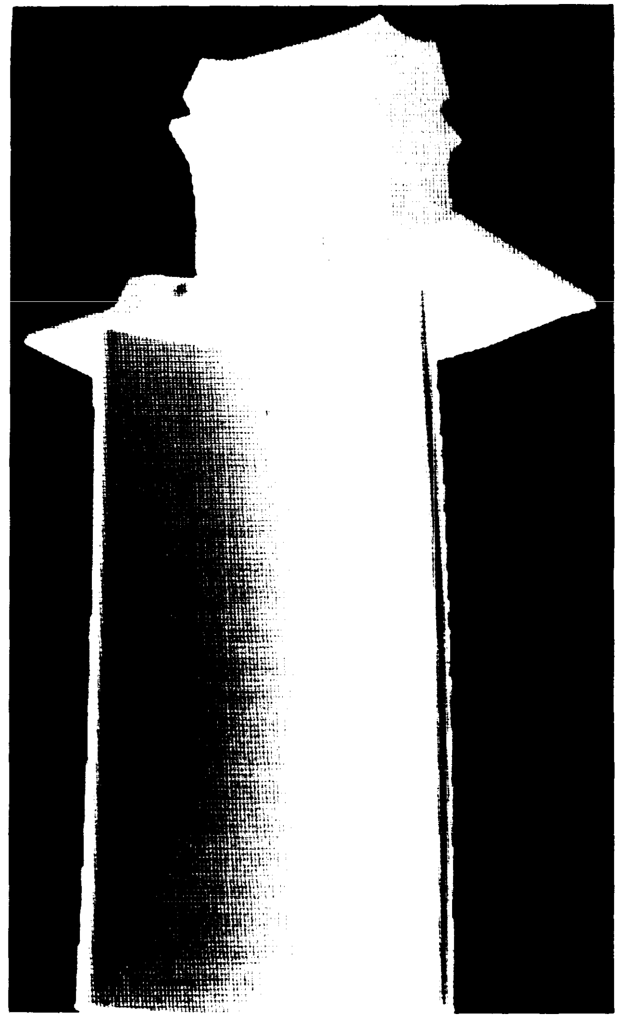


Photo credit University of Utah

A CAD image of a part from a system **based on "splines"**

CAD as Part of Computer-Integrated Manufacturing. –Perhaps the most important research theme involves connecting computer-aided design to other computerized systems in the factory. Such connections would mean, for example, that design information could be forwarded directly to machine tools that make the part, that designers could draw on previous designs as well as data on their performance and cost, and that designers would have up-to-date information on the manufacturabili-

[34] R. Reisenfeld, professor of computer science, University of Utah, personal communication.

ty and cost of their designs. Such comprehensive connections between design and manufacturing are currently far beyond the state-of-the-art.

There has, however, been modest progress toward interfaces between CAD devices. The Initial Graphics Exchange Standard, developed at the National Bureau of Standards under U.S. Air Force sponsorship, allows different CAD systems to exchange data (see ch. 8). However, while interfaces between computer-aided design systems are becoming easier, there is as yet little progress in allowing CAD and CAM systems to communicate. In some cases these devices can be wired together into a computer network, but establishing an effective interface requires sophisticated software to manipulate manufacturing information so that it is useful for designers, and vice versa.

Movement toward design-manufacturing connections is impeded by a strong tradition of separatism among design engineers and manufacturing engineers. A common description of the relationship is, "The design engineer throws the set of drawings over the wall to manufacturing. " There is evidence that such barriers are beginning to break down, slowly, as the need for communication has become apparent, and as engineering schools have begun to broaden the connections between design and manufacturing curricula.

There are many research efforts whose ultimate goal includes such connections between CAD and other manufacturing systems. These research programs include the Air Force's Integrated Computer Aided Manufacturing project, as well as the National Bureau of Standards (NBS) National Engineering Laboratory and a joint West German/Norwegian effort (see ch. 9). The heart of the latter effort is an attempt to use a very advanced geometric modeling system developed by the Technical University of Berlin as the basis for developing software which would allow design to be connected to all aspects of the manufacturing process. In addition, users of PA, such as GE and IBM, are also working on interface issues. However, full integration still seems at least a decade off.

Robotics

Robotics research is currently an area of intense interest in both industry and universities. There are a dozen or more universities with significant ongoing research projects in robotics, and perhaps 3 dozen industrial firms and independent laboratories. Government labs at NBS, the National Aeronautics and Space Administration (NASA), and several at DOD, are also involved.

In part because of the technical immaturity of robotics technology, and in part because it is a complex and interdisciplinary technology, there are many discrete areas of research problems and possible directions for extension of capabilities. The problem areas include:[35]

- *Improved positioning accuracy for the robot arm.* —Increased accuracy is essential for many applications of robots, particularly in assembly operations and other cases where a robot is programed offline. While current robots are precise (they can return to the same position on each cycle fairly reliably, within perhaps 0.005 inch), their accuracy (the ability to arrive at a predetermined point in space), is not nearly so reliable. Several techniques are being used to increase accuracy in robots. Though the traditional answer has been to increase the stiffness and mechanical precision of the manipulator arm, such approaches can greatly increase the weight and cost of the unit. Software calibration, a technique being developed at the NBS, involves adjusting the robot electronics to compensate for inaccuracies in its movements. Another technique involves using machine vision systems to "watch' the robot in action and correct its movements as they occur-this technique could potentially improve both accuracy and precision. Of the two, software calibration is far simpler technically and is likely to be available far sooner.

[35] J. S. Albus, " Industrial Robot Technology and Productivity Improvement, " *Exploratory Workshop on the Social Impacts of Robotics: Summary and Issues* (Washington, D. C.: U.S. Congress, Office of Technology Assessment, OTA-BP-CIT-11, February 1982), pp. 62-89.

Increased "grace, dexterity, and speed." —The physical structure of the manipulator—its material, actuation mechanism, and joints—has remained substantially the same for several decades. Several groups of researchers, sponsored by NASA and the Defense Advanced Research Projects Agency (DARPA), among others, are working on lighter structures for the robot arm. These would most likely consist of composite fiber materials similar to those now used extensively on aircraft-about one-sixth the weight of steel. Though the technology for such structures exists, composites are extreme ly expensive and the cost is holding back further use in robotics. Other directions for progress in robot structures include fundamentally different designs for the manipulator arm. A Swedish group has developed an arm which is structured in some ways like a human spinal column, while other research is directed toward using "tendons" to effect movement of the arm, as in the human musculoskeletal interaction.

Cost is not the only drawback to the use of lighter structural materials. In addition, the robot's controller must become more sophisticated in order to direct the motions of a lightweight, and inherently somewhat flexible, robot arm. For instance, computer scientists and mathematicians must develop control algorithms that will prevent backlash–i.e., the "play' or vibration that occurs when the arm is moved quickly from one position to another.

Finally, gripper design needs to be made more flexible. Directions for progress in grippers include both developing "hands" that can be used to manipulate a wider variety of objects, and also developing "quick-change" grippers so that the robot can autonomously exchange one "hand" for another.

- *Sensors, including vision, touch and force.* –Because sensors can be applied to a wide range of programmable automation devices, they will be addressed in a separate section later. One problem relevant to robots is the development of control systems that can accommodate sensory information. Systems are only now beginning to become available that can accept feedback from various kinds of sensors. In part, these systems have developed in conjunction with new generations of robot programing languages, to be discussed below. A continuing tension in development of robots is whether one should structure the robot's environment so that it does not need extensive sensing, or try to provide sensors to enable it to cope with an unstructured environment.
- *Model-based control systems.* —The most advanced and versatile controller for a robot would be one that had an internal model of its environment. In other words, it would have a store of information about the three-dimensional world, what the objects it worked with were supposed to look or feel like, and the rules for how physical objects interact with each other. Although this problem has intrigued many technologists, who view it as one of the ultimate solutions for expanding robot versatility and "intelligence, it is extraordinarily difficult to impart such information to the machine, and even to decide how one might structure such information.

Software. -Methods for programing robots are becoming easier and more efficient, although there is still substantial work needed in this area. Two languages have been released recently–IBM's A Manufacturing Language (AML) and RAIL, by Automatix–which are considerably more powerful than traditional robot languages, and which permit more sophisticated programing techniques, similar to advanced general-purpose computer languages such as PASCAL or ADA. Most other programing languages currently available are rather cumbersome and inflexible by computer-industry standards. At the same time, teaching-by-guiding programing is becoming less practical for complex applications; it delays production and has very limited capabilities for editing the program or using sensory information.

There is still much progress to be made in human interfaces with robots—the design of languages and programing systems that can be most easily and effectively used by humans. One technique for improving human interfaces, which has just become available, is the use of CAD to program robots and simulate their operation. The ability to visualize the robot's path may permit more effective planning and and debugging of programs so that production need not be stopped in order to test a robot program.

Interface standards. — Standards need to be developed for communication of information between robots and machine tools, sensors, and control computers. While such standards are a tractable problem, programmable automation producers, as well as the computing industry, are only beginning to make progress in establishing standards, and the standards-making process is long and intricate. In the meantime, efforts to establish interfaces between robots and other automated devices are hindered by a lack of standards. Researchers at NBS report that some manufacturers refuse to divulge details of the operation of their equipment that

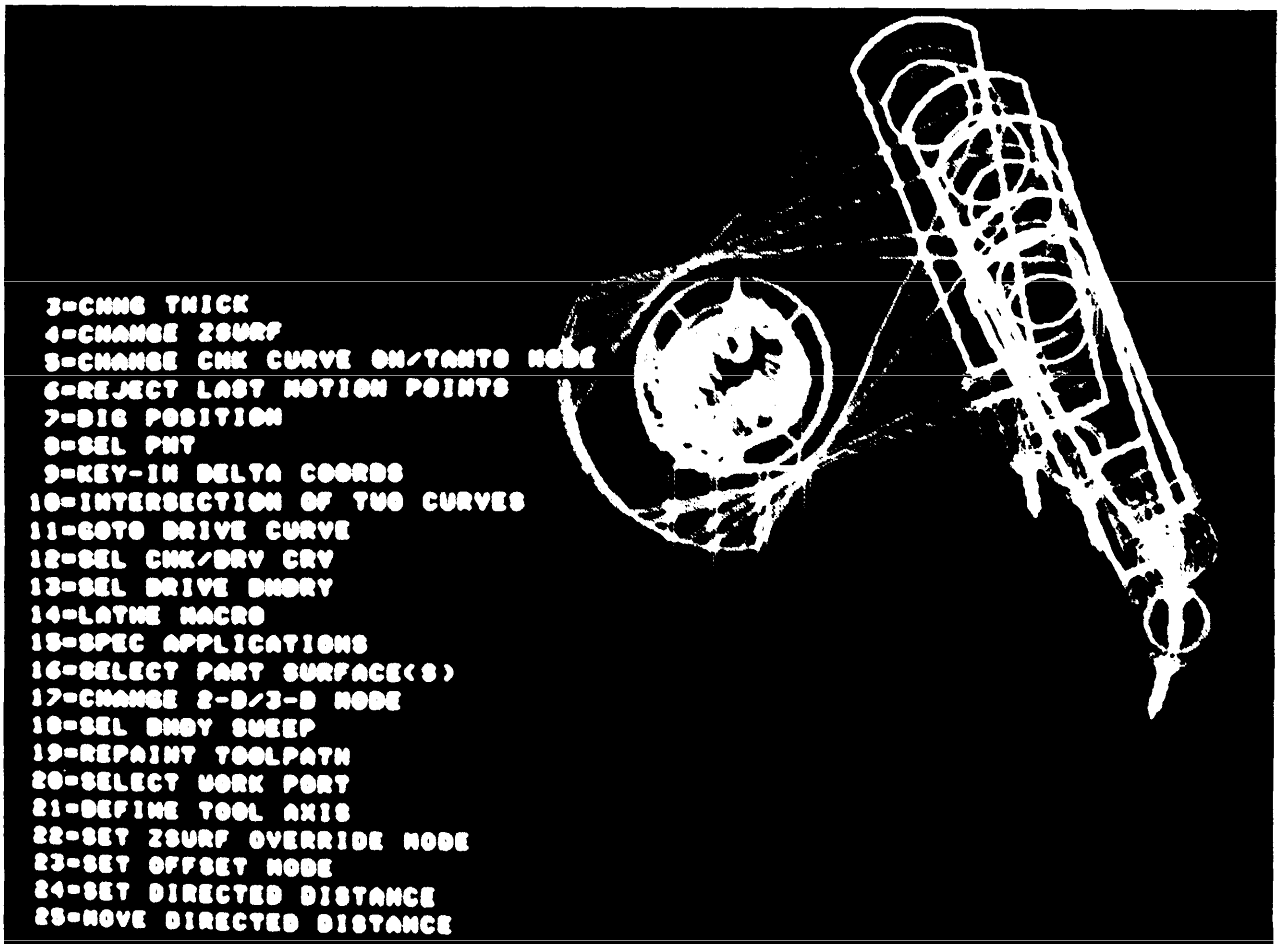


Photo credit Computervision Corp

A CAD-based simulation of a robot's operation would enable the equipment to be linked to other computers. (See the following discussion of standards and interfaces.)

- *Mobility.* –While techniques for limited movement along rails are already available for robots, the more general problem of developing a robot that could navigate its way through a cluttered factory is far more difficult. There is some argument about whether such mobility is even necessary for the factory-some would assert that such technology is too esoteric for the factory, and the plant should instead be organized so that mobility is unnecessary. There is substantial research in mobility, however, in large part sponsored by DOD agencies for specific battlefield applications.

Numerically Controlled Machine Tools

Although machine tools are a well-established technology, there continues to be a need for substantial improvements in the tools and their controllers. A "Machine Tool Task Force, " operating under the auspices of DOD's Air Force Materials Laboratory, issued a report in 1980 calling for hundreds of improvements and new research efforts. Among the ones most relevant to this study are those listed in table 10.[98]

"Machine Tool Task Force, "Technology of Machine Tools: A Survey of the State of the Art" (Livermore, Calif.: Lawrence Livermore National Laboratory, October 1980)

The bulk of machine tool R&D takes place in the laboratories of machine tool and controller manufacturers. A smaller but significant amount of work is undertaken at university mechanical engineering departments, with funding from industry or the Federal Government. The chief research problems can be divided into those involving the machine itself, and those involving the controller.

The *Machine* Tool.–Many of the development needs for machine tools involve devices which facilitate the use of the tools under computerized control. For example, chip removal –disposal of the metal shavings that accumulate in large volume during machining-is a big problem in industry, a problem that gets bigger as machines get more efficient and more automated. Various schemes have been used for chip control and disposal, none of which are entirely satisfactory. Many engineers believe the answer is not to create the chips in the first place—by forging the part close to its final shape, for example, or machining with lasers instead of cutting tools. While "near net shape" forging is becoming more prevalent, laser machining is still immature, and not yet practical for widespread applications.

Another problem in machine tools, whether automated or manual, is tool wear. A drill bit or grinding wheel has a fixed useful life, after which the quality of cut begins to decline and the tool eventually fails. The traditional solution to tool wear is simply for an experienced

Table 10.—Machine Tool Task Force Recommendations for Improving Machine Tool Controls

Area of improvement	Hardware (H) or software (S) development	Objective
Toolsetting	**H/s**	**Reduce setup time, improve accuracy**
Diagnostics and sensors	**H/S**	**Allow more of the important parameters** to be sensed and monitored for failure identification
Fixturing/clamping	H	More versatility of fixture and less setup time
NC programing and instruction	S	Develop improved new computer subroutines to simplify and reduce time for programing
Programmable controls	H	Integrate machine processes into computerized system; enhance conventional machine operations; provide interfacing devices and flexibility
Interface standards	H/S	Improve upgrading and growth-retrofit potential; interchangeability

SOURCE Machine Tool Task Force, Technology of Machine *Tools,* October 1980 machinist to listen to the machine tool and, ideally, sense when noise and vibrations become abnormal. In situations where that is not possible, particularly on CNC machine tools, machinists replace the tool after a specified period of tool life. In addition, the Japanese are said to run their machines at slower speeds in order to minimize tool failure during unmanned machining. However, tools can fail at almost any point in their use—a drill bit may fail after it only drills a few holes, or it may last for hours. This variability makes prescheduled replacement difficult and inefficient. There has been some progress in developing devices that can sense tool wear and report when tool change is needed. The National Bureau of Standards, for example, has a prototype device that "listens" to the vibrations produced by the tool and can be "taught" to recognize abnormal vibrations.

The rate at which a machine tool can cut metal depends on many factors—the type of metal, the depth of cut, the condition of the tool, and so forth. Controlling the speed of cut or the feed rate so as to cut metal at optimum removal rates has been a continuing research and development problem in the industry. As with sensing tool wear, the traditional answer has been for experienced machinists to adjust a cutting speed or feed rate dial on the machine. In the past decade, various "adaptive control' devices have been developed which vary the "speeds and feeds" of the machine tool based on motor load, for instance. However, these devices have had uneven reputations for effectiveness and reliability.

Finally, a great deal of effort is now being devoted to increasing precision in machine tools. The Navy's precision manufacturing program will be described in chapter 8.

Related to improvements in precision, a long-term goal for machine tool technology involves measurement of parts during machining. With such a scheme, quality problems could be identified and corrected during manufacturing rather than afterwards, thereby reducing waste. NBS has done some preliminary research on such a system of on line metrology at machine tools, although commercial use of such systems is limited to very simple and predictable part geometries.

Machine Tool Controllers. -As with all other forms of programmable automation, there is continuing demand for and research on simplifying programing of NC machine tools; the same holds true for the need to simplify and set standards for interfaces—between machine tool and controller, between machine tools, and between machine tools and other automation devices. A critical issue is the development of effective interfaces between CNC machines and other computerized devices, so that, for example, CNC machines can derive their cutting instructions from the stored dimensions of a design produced with CAD. This is now possible only in specific limited situations, where tremendous effort has been devoted to developing the interfaces for a particular application.

Flexible Manufacturing Systems

Flexible manufacturing systems for the machining of prismatic parts are becoming more prevalent, and are a relatively established technology. FMS for rotational parts are just beginning to be available, while the range of other possible applications for FMS—grinding, sheet metal working, or assembly—are not beyond the reach of current technology, but are only at early stages of development.

Many of the chief R&D problems for FMS involve logistics: design and layout for the FMS, and computer control strategies that can handle sophisticated combinations of powerful machine tools. In addition, there is a need for more sophistication in simulation systems for the FMS so that their efficiency can be optimized.

There are a variety of enhancements to FMS hardware which seem to be on the horizon. In addition to all of the developments described under the individual technologies, *these in*clude automatic delivery and changing of cutting tools, and systems for automatic fixturing and refixturing of material to be processed.

Improving the reliability and versatility of materials handling systems is also an important need for FMS. As mentioned earlier, the level of sophistication in materials handling technology often does not match that of other PA technologies, and the AMH system may be the "weak link" in the FMS.

Computer-Integrated Manufacturing

Computer-integrated manufacturing receives substantial attention in industry discussions and trade journals, though there is relatively little active R&D at this level of the computerized factory. This is at least partly because there is not yet substantial demand for CIM systems. GE and IBM have begun to work on computer-integrated manufacturing, as have some Japanese firms, particularly Hitachi, and a coalition of laboratories in West Germany and Norway. The Automated Manufacturing Research Facility at NBS is perhaps the largest test bed for CIM techniques. It is described in more detail in chapter 8.

As with FMS, one of the key issues in CIM development involves the logistics of a complicated factory. Several groups, including NBS, the U.S. Air Force ICAM project, and Computer-Aided Manufacturing International (CAM-I), have been working on "architectures" for such an automated factory. Figure 10 is an example of such a conceptual framework for CIM which forms the foundation for detailed work on factory control architectures.

One of NBS's major contributions in automation R&D has been in developing strategies for the interface of programmable automation devices. Their emphasis has been on what they call a "mailbox" or decentralized approach to factory communication and control. In such a system, the control of the factory is distributed at different levels among the various PA devices (see fig. 10). For example, a factory-level computer might send a message to a pro duction-level computer—' 'Make 150 of part number 302570. " The production-level computer would then send a message to the "mailbox" of a certain work cell-" Execute production plan for part 302570, 150 times. " In turn, the work cell controller would send messages to the mailbox of the machine tools and robots in the cell, to execute certain programs stored in their memory.

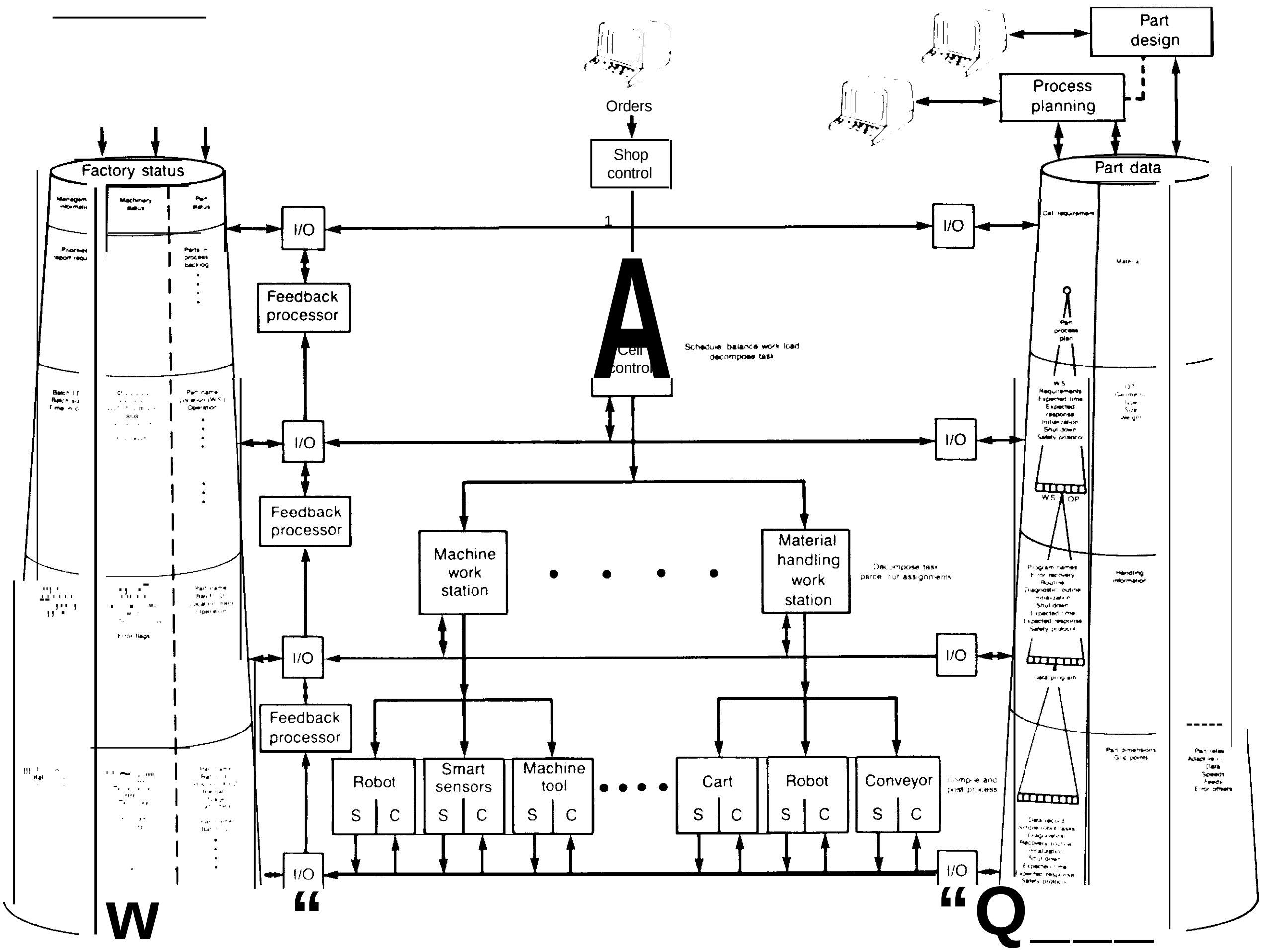
The "mailbox" approach differs from a centralized, or "star," approach to automated systems control in which a central computer directly controls each action of every machine in the factory. The advantages of the mailbox system are that it simplifies standards and interface problems—the only interface standard necessary is for the location of the mailbox in which to deposit messages. This allows one robot to be substituted for another, for example, with relative ease. The mailbox approach allows different PA devices to operate using different languages and proprietary operating systems, as long as they are able to interpret messages from the computer controller.

Hierarchical arrangements for automated manufacturing, such as those illustrated in figure 10, tend to involve a large number of separate computers, each with separate data bases. Techniques for "distributed data base management, " that is, managing and manipulating data in several computer systems simultaneously, need to be developed in order for a hierarchical arrangement to be practical. Similarly, techniques and standards for establishing communication between computerized devices, both in-plant and between plants, need to become much more sophisticated.

A group of researchers at Purdue University, in collaboration with several large manufacturers, is attempting to exploit currently available technology to design an actual factory with maximum computer integration. The leader of that effort argues that the technology for CIM is available, and that technical advances, though welcome, are not necessary. Rather, he argues that factors holding back "fully" automated manufacturing are primarily:

1. the lack of standards for interfaces, communication networks, and programing languages;
2. a need for more powerful data-base management systems;
3. the need for detailed mathematical

Figure 10.—NBS Scheme for Distributed Factory Control



SOURCE PJatl~nal Burpab of Standards

models of physical and chemical processes;

4. shortages of technical personnel;
5. shortages of computer power; and
6. manufacturing management who are unaware of the detailed technical benefits of automation.[37]

Technical Trends and Barriers: Cross-Cutting Issues

The following issues are not primarily connected to a particular automation technology, but rather have a large potential impact on the current and future capabilities of automation technologies as a whole.

Artificial Intelligence*

Artificial intelligence (AI) is a loose conglomeration of research areas united by the common goal of designing machines which can perform tasks we would generally regard as requiring intelligence. It is significant for programmable automation because many experts look to AI techniques as the key to automating parts of the manufacturing process here-

[17] T, Williams, Purdue Laboratory for Applied Industrial Control. "Information Systems Technology and Automation: Its Present Day Status and a Prognosis," paper developed for the American Society of Mechanical Engineers Winter Annual Meeting, Boston, Nov. 15, 1983.

*A forthcoming OTA report, "Information Technology Research and Development," will discuss artificial intelligence in more detail.

tofore thought to be too complex for automation.

The core of basic, long-term AI research includes work on imparting such intelligent characteristics as learning, reasoning and planning to computers. Building on some of this work are several more applied research areas: the most sophisticated end of the robotics field; the development of systems for image processing–deciphering images from video cameras or touch sensors; development of techniques to allow the computer to understand natural language (e.g., English, as opposed to computer languages such as FORTRAN), both written and spoken; and expert systems, programs which can, through a sophisticated network of rules, advise or make decisions in specific situations much as a human expert would.

While robotics and sensors (image understanding) have been largely covered elsewhere in the chapter, natural language and expert systems both have significant potential applications for manufacturing in this decade.

Commercial systems for processing both written and spoken language have received substantial attention in the past 5 years. The hope for both kinds of systems is that, by allowing people to give commands and communicate with computers in everyday language, widespread use of the computer will be substantially easier. Fewer people would need to learn specialized computer languages, and fewer computer experts would be needed as intermediaries between computers and those who wish to use the computer as a tool.

The primary application for computer processing of written language has been in the development of so-called natural language front ends for data-base management systems (DBMS). In such a system, the data base–e.g., sales records for a company—and the DBMS itself used to manipulate and summarize that data, remain essentially the same. However, the natural language "front end" allows users to type questions in relatively free-form English, and translates those questions into the specialized language used by the DBMS.

For example, without a natural language front end, a plant manager who sought the answer to the question, "Which products in the 2000 series were sold in volumes of more than 1,000 last year?" would probably refer the question to a programer, who would write a short program in a computer language to process the request.* With a natural language feature added to the DBMS, that plant manager could type his request, more or less exactly as he would say it, into a computer terminal, and the requested information would appear on the screen.

In general, though, scientists have found natural language understanding to be a much greater challenge than originally expected. Because there are so many ambiguities and unclear references, understanding everyday language requires substantial information about the context of a given statement or question, and the world in general. Organizing such information to allow natural language understanding by computer has proven to be an extremely difficult task, in part because of our very incomplete understanding of how people store and manipulate such information.

In practice, this means that constructing a natural language front end for a DBMS requires weeks or months of work in writing code that sets forth for the computer the various meanings of the terms used for a particular application, and the possible ways they can be combined. Although many such systems can interpret relatively freeform questions, they are also severely constricted in subject area. In other words, the same system which can interpret questions about a firm's sales cannot decipher queries about the design of its products.

*In one DBMS language, such a (very simple) program fight look like:

```
OPEN SALES 83:
FIND ALL
FIND PRODNO GT 1999 AND LT 3000
FIND SALESVOL GT 1000
LIST PRODNO, SALESVOL
```

Systems for computer processing of spoken language present a different set of problems. These involve techniques for analyzing the electronic signals produced by a human speaking into a microphone, and comparing them to signal patterns stored in computer memory. Voice recognition systems have been developed which are capable of interpreting perhaps 100 words, spoken distinctly and usually by a speaker to which the system has been "trained" to listen. Such systems can be used, for example, to allow workers to give the computer simple commands when they do not have a hand free to use a keyboard. Various other uses have been proposed for such systems, from directing the motions of a robot to operating a CAD system, although the limited vocabulary and lack of flexibility of such systems has hindered widespread use. Rapid advances in hardware and software for voice recognition may expand their capabilities in the next few years.

Both for written and spoken language understanding systems, the limited breadth and flexibility of applications is a consistent theme. In fact, a general solution to the problems of natural language understanding-e. g., one that could impart to a computer the language understanding capabilities of a 5-year-old child—is probably at least two decades off.

Finally, expert systems can allow the use of computers in situations normally thought to be so complex that they require human judgment or ''intuition. AI researchers have found that in a narrowly defined problem area, it is sometimes possible to simulate much of the judgment of human experts by breaking down that judgment into hundreds of rules for the information to look for under different circumstances, and how to weigh that information.

Expert systems are typically composed of hundreds of rules, gathered by painstaking interviewing of human experts, about exactly how they make their judgments. The interview and development process for an expert system typically takes several years to complete, although it is becoming less time-consuming as techniques for developing the systems become more refined. The interview techniques used by expert system developers allow the systems to capture many of the subtleties of how an expert arrives at judgments.

Two of the classic expert systems, for example, are "Dipmeter Advisor, " developed by Schlumberger to offer advice on oil geology, and Stanford's MYCIN, which advises doctors on antibiotic drug treatment. Figure 11 is an excerpt from the rules upon which the MYCIN system is based. The system asks the doctor a series of questions about the patient, and then offers a diagnosis and treatment (see fig. 12). It can explain the rules it used to arrive at its recommendation, and physicians can also improve the system by adding new rules.

Some of the more recent applications of expert systems, closer to manufacturing, are a system which guides mechanics in the repair of locomotives (Delta/CATS-l, developed by GE), and a system which helps configure complex computer systems (XCON, formerly "R-l, " developed by Carnegie-Mellon University and Digital Equipment Corp.).

Though the commercialization of expert systems is only beginning, many industrialists have high hopes for their use in manufacturing. A myriad of applications have been proposed, including systems which could mimic the performance of a human machinist; systems for advising designers and preventing design errors; systems which would act as a linkage between manufacturing and design

Figure 1 l.– Sample Rule from the MYCIN Expert System

Rule 27

If 1) the gram stain of the organism is gram negative, and
2) the morphology of the organism is rod, and
3) the aerobicity of the organism is anaerobic,

Then: There is suggestive evidence (0.7) that the identity of the organism is Bacteriodes.

SOURCE R Davis and C Rich, Expert Systems Fundamentals tutorial at 1983 conference of the American Association for Artificial Intellgience

Figure 12.—Sample “Advice” From the MYCIN Expert System

[Rec 1] My preferred therapy recommendation is as follows:
In order to cover for items <13456>:
Give: GENTAMICIN
Dose: 128 mg (1.7mg/kg) q8h IV (or IM) for 10 days
Comments: Modify dose in renal failure
In order to cover for item <2>:
Give: CHLORAMPHENICOL
Dose: 563 mg (7.5 mg/kg) q6h for 14 days
Comments: Monitor patient’s white count

Do you wish to see the next choice therapy?
•* NO

SOURCE: R. Davis and C. Rich, Expert Systems: Fundamentals, tutorial at 1983 conference of the American Association for Artificial Intelligence.

data bases; and even systems for overall factory control.

Two researchers describe the characteristics of a problem area which makes a good domain for expert systems as one where:[38]

> There are recognized experts; the experts are provably better than amateurs; the task takes an expert a few minutes to a few hours; the task is primarily cognitive; the skill is (routinely) taught to neophytes; the task domain has a high payoff; the task requires no common sense.

It is unclear in this early stage of application of expert systems just how widely applicable these tools will be. While the successes to date have been impressive, each of the current systems has been the result of many years of effort in top AI laboratories. Furthermore, they have succeeded in very carefully selected, and very carefully restricted problem areas. For example, GE’s system for diagnosing locomotive problems cannot be used to diagnose automobiles, or even to diagnose different brands or configurations of locomotives without major alteration.

With current high levels of interest in expert systems, and evolving tools and techniques to streamline their development, it seems likely that these tools will be used in several areas of manufacturing. However, it is unlikely that expert systems will in the near future meet the many expectations which their recent successes have generated. It is easy both to underestimate the development effort and skills needed to construct such tools, as well as to imagine new applications in areas which are too broad or ill-defined for current technology to handle.

Sensing this problem, one recent National Research Council committee report warned of “unrealistic expectations:”[39]

> In an extremely narrow context, some expert systems outperform humans (e.g., MACSYMA), but certainly no machine exhibits the common sense facility of humans at this time. Machines cannot outperform humans in a general sense, and that may never be possible. Further, the belief that such systems will bail out current or impending disasters in more conventional system developments that are presently under way is almost always erroneous.

One of the dangers of high expectations for expert systems and other areas of AI is that if these expectations are unmet, there could be a backlash and loss of interest in AI. The field has already suffered from two or more such cycles of high expectations and loss of interest and credibility. Indeed, AI has long been an area in which claims and hopes are more prevalent than concrete successes, though current workers in this area seem to be rather more cautious.

Manufacturers are not alone in their high hopes for AI, as evidenced by Japan’s recent “Fifth Generation” computer project, and DOD’s new Strategic Computing project. Both of these programs are long-term, ambitious R&D in computer hardware and software in which AI plays a primary role (also see ch. 8). Another major goal of both programs is the development of “supercomputers.” Though the definition of supercomputers changes as

[38] R. Davis and C. Rich, “Expert Systems: Fundamentals, tutorial at American Association for Artificial Intelligence 1983 annual conference, Washington, D. C., Aug. 22, 1983.

[39] “Committee on Army Robotics and Artificial Intelligence, Manufacturing Studies Board, National Research Council, *Applications of Robotics and Artificial Intelligence to Reduce Risk and Improve Effectiveness: A Study for the United States Army* (Washington, D. C.: National Academy Press, 1983), p. 63.

the technology develops, a current working definition is machines that can process more than 100 million instructions per second. AI and supercomputers tend to be discussed together and often confused with each other. However, though both AI and supercomputers are at the frontiers of computer science, they are essentially separate research areas at this time. It is likely, though, that future AI applications will require advanced computer architectures-not high-speed number crunchers as much as machines designed to process Symbols and logic.

Although the infusion of DOD funds into AI may expand and advance the field, defense applications may also continue to monopolize the small pool of U.S. AI researchers. Despite the fact that DOD is making concerted efforts to encourage commercial spinoffs from the Strategic Computing project, most of the attention of the AI R&D community will be focused on military applications rather than commercial manufacturing applications.

Much of the current wave of commercialization of Al is based on AI research done as much as a decade or more ago. In many cases, commercial applications have recently become feasible because of the continuing declines in costs of computing power. While one can expect further improvements in available Al-Based tools over the next few years, these improvements may be small in comparison to this initial harvest. The more fundamental problems of AI, involving natural language systems of general applicability, versatile and unstructured machine vision, and—ultimateIY-–generally intelligent, perhaps "learning" machines, are still very much a long-term research issue.

Standards and Interfaces

The need for standards in both languages and interfaces is strong and consistent throughout programmable automation technologies. Without standards, it is very difficult to combine equipment of different vendors, and it is more difficult to proceed incrementally toward computer-integrated manufacturing.

The demand for standardization in languages is particularly strong from users of automation devices, because of the increased confusion and need for additional training that result from the many different programing languages.[40]

More likely than one standard language for manufacturing, however, may be a set of standard languages for each application. For example, there might be a standard language for arc-welding robots, another for materials handling systems. These could be either formally adopted or de facto standards (i.e., they become commonly accepted through usage or through the influence of major vendors or users in the field). For example, many of IBM products and techniques are treated as standards because the company has dominated the computer field. However, domination by a single firm in programmable automation systems is not as likely (see ch. 7). In addition, DOD has created many de facto standards, APT among them, through its procurement practices. It remains to be seen to what extent DOD's latest attempt at a standard computer language, ADA, will be applicable to manufacturing systems.

1n addition to standards for programing languages, standards for interfaces between computerized devices will greatly facilitate integrated PA systems. The recent development of standards for "local area networks, initially aimed to connect personal computers in offices, may also be useful in the factory. " Such standards define the hardware connections for hooking devices together, as well as the "protocols" that ensure that different systems can interpret each others' messages. However, the content of those messages depends on the architecture of the factory —i.e,, the different levels of control and the kind of information it is necessary to communicate. As discussed earlier, efficient architectures for integrated factories are only beginning to be worked out in manufacturing laboratories such as the Automated Manufacturing Research Facility at NBS.

[40]"OTA automation technology workshop, May 29, 1983.
[41]"Local Area Network Facilitates Factory Automation, " Tooling *and Production*, May 1983, p. 94. These networks are based on a professional association-developed standard known as IEEE802.

Manufacturers and others often argue that premature standardization will stifle innovation. It can tend to "freeze" a technology at a particular point in its development, and discourage further innovations which may be inconsistent with the standard. In addition, there is sometimes a strategic concern that standard languages cause more competition by permitting easier combination of PA devices from different manufacturers. One NBS official has argued that parts of the computerized controllers for machine tools, for example, are technically ripe for standardization but the machine tool manufacturers do not seem to support such a move.[42]

Apart from any resistance to standards, there is the fact that implementation of standards is voluntary in the United States, which is not the case in many other countries. As a result, development of a successful standard takes years of negotiation among manufacturers and users. To complicate matters, recent court decisions[43] have held organizers of standards efforts liable if a standard can be shown to hurt a particular company. This has made progress toward adoption of standards in many areas even more cautious and slow-going.

NBS staffers contribute to standards efforts by serving on and helping to coordinate the many private sector standards committees working on automation issues. Relevant efforts are being conducted by the Electronic Industries Association, the Robotic Industries Association, the American National Standards Institute, the American Society for Testing and Materials, the Institute of Electrical and Electronic Engineers, and the International Standards Organization.

Human Factors Research

In the past few years, makers of all computerized equipment have become aware of a need to design systems for optimal usefulness and productivity for their human operators. There are various terms used to describe the focus of such efforts: "user friendly" qualities and "man-machine interface, for example. * In part to help market their equipment, computer manufacturers have found that there are steps they can take to improve the human factors aspects. Human factors experts argue that research and testing of the effectiveness of a product must be undertaken throughout its design cycle. "Human engineering, which was seen as the paint put on at the end of a project, is becoming the steel frame on which the structure is built. "[44]

Although many experts agree on the importance of human factors, it has often been a neglected topic in research. It is frequently regarded as too basic for industry to examine, and too applied for university research efforts. Although DOD has pursued man-machine interaction research for decades, only recently has human factors become a subject of systematic study outside of DOD. Psychologists have developed testing procedures to help determine the human effectiveness of different designs. Recently, human factors of computer systems has become a strong and growing subfield of cognitive psychology.

Designers of programmable automation equipment have lagged behind the trend toward concern about human factors in computerized systems, in part because of the newness and small size of the market for many automation devices. In addition, some PA devices such as robots or portions of FMSS are often designed with the intention of minimal contact with humans.[45] Several systems de-

[42] R. Hocken, NBS, personal communication, Aug. 12, 1983. For example, some NC controllers only understand a number to be "two" if it is written as "2". Others require it to be written as "2.000" or "2. .E00". This can cause difficulty in trying to move programs from one machine to another, even if the machines ostensibly use the same language.

[43] In *American Society of Mechanical Engineers v. Hydrolevel Corp.* 102 S. Ct. 1935 (1982), the Supreme Court held that a standard-setting organization was liable for the antitrust violations of participants in the standards-making process when they acted with the apparent authority of the ASME.

* A Variety of terms by used by researchers industry to describe human factors and related subjects. Some others not mentioned in this section include software psychology, user science, and human-computer interaction.

[44] B. Shneiderman, "Fighting for the User, " *ASIS Bulletin*, December 1982, p. 29.

[45] H. M. Parsons and G. P. Kearsley, "Human Factors and Robotics: Current Status and Future Prospects, " Human Resources Research Organization, October 1981.

signers have noted, in fact, that the systems with the worst human factors seem to be those which were designed to be unmanned, but later determined to need an operator or monitor. Computer-aided design is somewhat different from other PA technologies in this respect. Because of the larger size of the market and the recent attempts to develop lower cost systems for noncomputer users, CAD designers have begun to pay attention to designing systems that operators can use more easily and productively.

There are essentially two levels of human factors research. The first, sometimes known as "ergonomics, " aims to make people more physically comfortable and productive while working at a machine. For example, it includes research on the ideal levels of light, color of display screen, size and configuration of keyboard, etc. A second level looks at more fundamental questions in "human-machine interface, " such as how to distribute control between operator and machine, how to design software for optimum productivity, and how to maximize operator satisfaction. Most such work has been directed toward general purpose computers or word processors rather than programmable automation.[46]

These research areas are related to larger questions in industrial psychology and management concerning less tangible issues such as the impact of technology on the work environment and/or on the design of jobs. There has been little systematic work in the United States in these areas, although there is substantial research in some European countries. "

[46]There has been substantial work, however, in the design of systems for teleoperators — remote manipulators controlled by a human operator. Such work is often aimed for ultimate applications in unmanned space missions or underseas, handling of radioactive material, or battlefield applications, See, for example, T. N. Sofyanos and T. B. Sheridan, *An Assessment of Undersea Teleoperators* (Cambridge, Mass.: MIT Sea Grant College Program, June 1980).

[47]See, for example, H. H. Rosenbrock, Professor of Control Engineering, University of Manchester (U. K.) Institute of Science and Technology, "Robots and People, " *Measurement and Control,* March 1982, pp. 105-1 12; P. Brödner and T. Martin, "Introduction of New Technologies into Industrial Production in F. R. Germany and its Social Effects-Methods, Results, Lessons Learned, and Future Plans, " Proceedings *of the Eighth Triennal World Congress of the International Federation of Automatic Control,* Kyoto, Japan, Aug. 24-28, 1981, pp. 3433-3445; Swedish Work Environment Fund, *Programme of* Activities and Budget, 1981/82–1983/84. For further detail see ch. 5.

Sensors

The vast majority of programmable automation devices are limited in their capabilities because they are "unaware" of their environment. To use anthropomorphic terms, they do not "know" what they are doing, exactly where their parts are, or whether something is wrong in the manufacturing process. * This problem is especially acute when manufacturers hope to use PA devices to perform tasks normally performed by people. A minor adjustment or observation which would be easy and obvious for a human-e. g., righting a part which arrived upside-down-is nearly impossible with most current robots.

Hence, computerized devices that can acquire information about the environment are a lively area of inquiry. While many of these devices are used in conjunction with robots, they can also be used with other CAM equipment—e.g., NC machine tools or AMH systems–or independently. There are roughly three categories of applications for sensor systems: 1) inspection, in which parts or products are examined and evaluated according to preestablished criteria; 2) identification, in which parts, products or other objects are classified for purposes of sorting or further processing; and 3) guidance and control, in which sensors provide feedback to robots or other CAM devices on their position and the state of the part or product.

One can simplify the range of sensor technologies by dividing the devices into three classes according to their complexity. While all of the devices are used for guidance and

*There are some exceptions where PA devices do have significant information about their environment. One obvious exception is the Coordinate Measuring Machine, built specifically} to measure the dimensions of objects, Another is in factories which cod each part, for example, with optical codes similar to those used on groceries. optical code readers at each machine can identify the part in process. Finally, many PA devices do have *internal* sensors. For example robots and machine tools have sensors which provide feedback on the positions of their joints, control applications, usually only the most complex (i.e., vision and touch sensors) can handle inspection and identification tasks.

The simplest devices provide binary information—e.g., a weight sensor, photocell, or simple electrical switch can indicate whether a part is or is not present. These simple sensors are relatively cheap, technologically mature and easy to implement. They are already used widely in manufacturing equipment, and their use will undoubtedly continue to grow for applications in which binary information is useful.

At a moderate level of complexity, the information sensed is analog (continuously varying). For example, a proximity sensor can determine the distance of an object. A popular proximity sensor used as a safety device on industrial robots is the same as the one used on Polaroid SX-70 cameras. It calculates distance by emitting inaudible sound waves and calculating how long they take to bounce off the closest object and return. For safety purposes, these can be used to stop the motion of the robot if a human enters its "work envelope." Other sensors in this moderate level of complexity include devices which can electromechanically sense force and torque—e. g., in a robot arm or a machine tool spindle. These can be used, for example, to allow a robot gripper to apply just enough force to a delicate object. Finally, many devices for measurement fall into the moderate-complexity category. Optical sensors, for example, can be used to monitor the diameter of a driveshaft on a lathe, or for noncontact sensing of the dimensions of hot metal as it emerges from forging processes.

Most of these moderately complex sensing techniques are fairly well-developed, and can be applied relatively easily albeit with some customization. There is a moderate amount of It&D under way to increase the quality of information from these devices (e.g., their sensitivity and speed), and to increase their range of applicability (e.g., development of sensors for measuring arbitrary prismatic shapes on machine tools). In addition, the coordination of these sensors with each other and with CAM tools is a very difficult problem. Computer scientists are attempting to develop processing techniques that can quickly interpret force and torque data from the various joints of a robot, for example, and provide feedback to the robot's controller.

At the most sophisticated end of the sensing techniques, visual and touch sensors deal with information that is not only analog but also needs substantial processing to be useful. Vision and touch sensing technologies are only in their infancy, and have just begun to have practical uses in the factory. Of the two, vision by far receives the most attention.

The chief technical problem in machine vision systems is in interpreting the pictures generated by a video camera. In a typical vision system, a frame—i.e., one complete image frozen in time— is typically composed of 256 by 256 picture elements, or pixels. If each pixel is either black or white, then there are more than 65,000 bits of information that the computer program must process. In general, the steps in the process include:[48]

- Segmentation.—The areas of the image must be clarified and divided into segments or "blobs," representing the features of the object and its background. There are two general schemes for beginning the interpretation of the data. One makes use of discontinuities-prirnarily detecting the edges of the object in the image. The other approach relies on similarities in the image, i.e., areas of the image that are of similar intensity.
- *Recognition.–The* system must compare the features (segments) it has identified with those stored in its memory, attempt to find an object in its memory that is suitably close to the one in the image, and hence label the object and its features.
- *Interpretation.* –This step varies depending on the machine vision application. For

[48] J.M. \\"right, "Vision of the Future," unpublished manuscript, Carnegie-Mellon University Robotics 1 nstitute, January 1983.

robot guidance, the interpretation step might be to identify the object, then calculate its coordinates so that the robot can grasp it. For an inspection application, the interpretation of the image might be to determine whether the object has the right dimensions or is free of defects.

In the vast majority of current vision systems, each picture element in the 256-by-256 element image is either black or white. In more advanced systems just beginning to be used in industry, each pixel can be one of several shades of gray. These systems, often called "gray-scale, are potentially more powerful in their ability to identify objects and cope with uneven lighting, but they also require much more computer power and algorithms for processing data which are only beginning to be worked out. Systems for processing color images are another order of magnitude more complex, and there is no active work on such systems yet.

The systems described above essentially provide 2-D information, although certain tricks can be used to infer the 3-D characteristics of an object. Some researchers have used more than one camera in order to obtain 3-D information much as the human eye does, though such schemes are in very early stages. One very promising method to obtain 3-D information is the use of "light striping" systems. In such a system, a laser or other light source flashes a very precise band of light onto an object, and the camera records the image at that instant. By examining how such structured light bends over a 3-D object, the system can infer the dimensions and distance of the object.

Current machine vision is in a very early stage. The range of objects that can be iden-

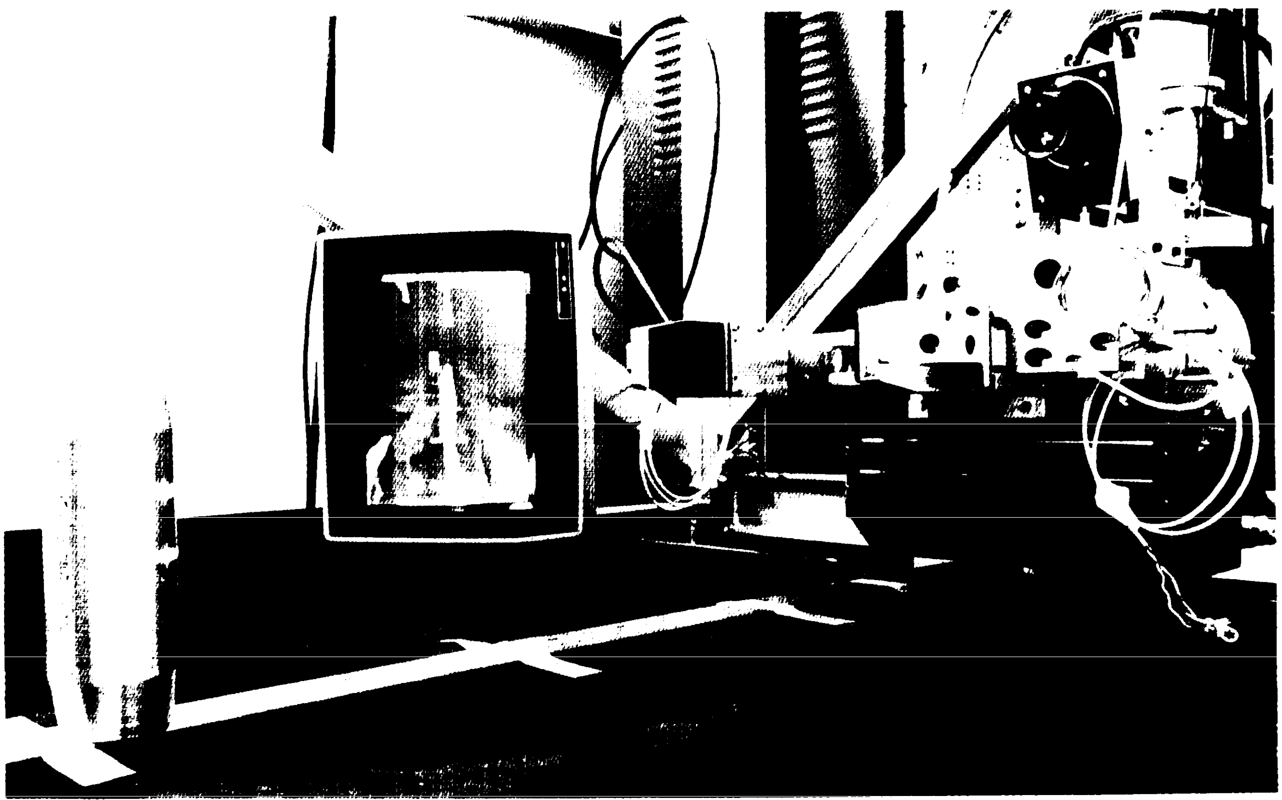


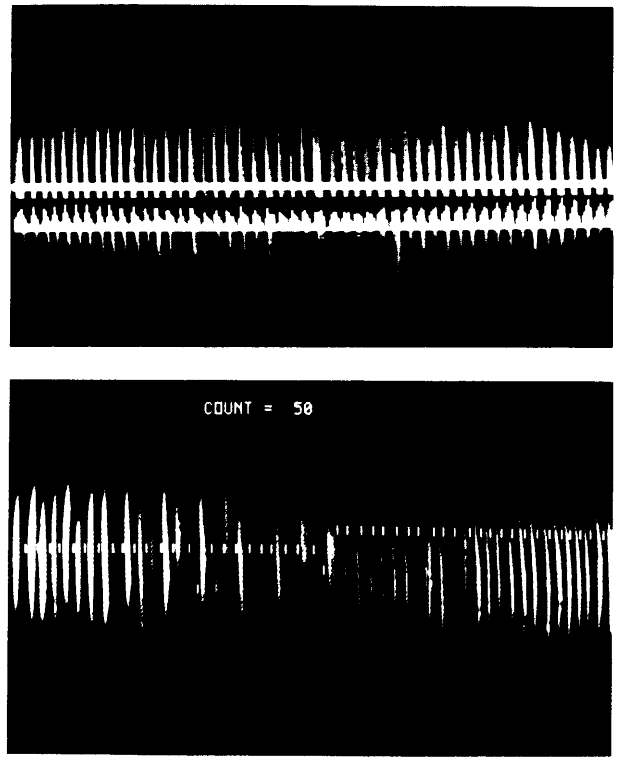
Photo credit National Bureau of Standards

"Light striping" system can determine the shape of a 3-D part by flashing a very precise line of light (from slots on right, below gripper) and photographing how that light is bent by the object. TV monitor shows view of camera above gripper tified, the speed of the interpretation, and the susceptibility of the systems to lighting problems and minor variations in texture of objects are all examples of serious problems with current technology. Successful applications of current machine vision technology tend to be very specific, ad hoc solutions, often using clever “tricks” or manipulations of the manufacturing environment. As one report notes, “The vision systems of today, and those for the rest of the decade will not promise great generality. These sorts of tricks will be an important part of the field for many years to come.”[49] Nevertheless, many useful applications are possible with existing technology and machine vision is currently a rapidly growing field. In certain specific applications, especially very tedious tasks such as inspection of electronic circuit boards, machine vision systems can outperform humans.

An example of a successful machine vision application is shown in figure 13. Here, a system developed by Octek Corp. counts stacks of cups prior to packaging. The system first “grabs” an image from its camera under controlled lighting conditions, defines the edges of the cups, attempts to eliminate shadows and other confusing data, and counts the number of cup lips. Similar programs have been developed to inspect cassette tapes and circuit boards.[50]

While there is considerably less research effort under way on touch sensors, there are several groups of researchers, for example, working on a touch sensor based on a carbon-impregnated rubber pad which changes its electrical conductivity under pressure. This pad could be attached to a robot gripper, and it would send to the computer processor an image or “footprint” of the object being grasped. Once this image has been obtained, interpreting it involves virtually the identical process used for vision processing.

Figure 13.— Machine Vision Process



Two steps in a machine vision process developed to count stacks of paper cups for a cup manufacturer. The cups are lit by a highly directional fiber optics light source, which makes their edges stand out. The top photo shows part of the system’s segmentation process, in which it assesses the intensity of light for each cup lip. The bottom photo indicates the interpretation function, in which the system has counted the number of cups in the stack. Note the shadows and relative unevenness of light which complicate even this simple machine vision application.

SOURCE: Octek Corp.

There seem to be two schools of thought on sensors for industrial robots. One argues that, if enough care is taken in organizing the manufacturing environment, complex sensors are unnecessary. Parts can be carefully fixtured so they are in the proper orientation and position, and sensors in the simple or moderate levels of complexity will suffice. The other point of view is that robots should be able to adapt to the chaos of manufacturing, and should ideally have senses—vision, in particular-which rival those of a human.

Materials Trends

Plastics, ceramics, and composites are replacing metals in a wide variety of products

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[49] Ibid.

[50] D. L. Hudson and J. D. Trombly, “Developing Industrial Applications for Machine Vision,” *Computers in Mechanical Engineering*, vol. 1, April 1983, pp. 18-23. Note that this application of machine vision, like many inspection applications, is not used in connection with a robot.

at an increasing rate. This trend is both complementary to and problematic for increased use of certain PA devices.

These new materials technologies, on the whole, fit well into an environment of computer-integrated manufacturing. Injection molding of plastics, for instance, is by nature an automated process and adapts easily to integration with other computer-controlled devices. It is thus possible to create a "flexible manufacturing system" for plastics at least as easily as for metals.* Similar systems are also possible for producing parts from new-technology "fine grain ceramics," which have strength comparable to that of metal (at a fraction of the weight), are immune to corrosion, and do not have the brittle qualities that one expects from ordinary ceramics.

*One hitch in creating an FMS for plastics is in developing dies (the metal forms into which molten plastic is injected) which are "programmable" or easily changed. Several researchers are currently working on this problem.

These trends and others mean that the amount of metal-removing activity is going to decrease. Thus, there is some chance that use of plastics and ceramics will eventually render obsolete some new *metalcutting equipment.* This possibility has not yet been examined systematically by the metalworking community. Robots, because of their flexibility, are less likely to be affected than machine tools. However, there are certain factors that tend to make widespread obsolescence of new metalworking equipment unlikely. First, metalworking machines have useful lives of 30 years or more, and the users of this equipment move notoriously slowly in replacing machine tools. As new materials technologies do reduce the amount of metalworking, it is the vast stock of older, manual machine tools that is likely to be useless rather than the newer equipment. Second, it is expected to take at least two decades for ceramics to displace a significant amount of metalworking.

Future of the Technologies

Capabilities

Building on the "Trends and Barriers" section of this chapter, tables 11 through 15 summarize the main problems for PA technologies and the projected times for solution. Though these projections must be considered extremely tentative, they provide a sense of the relative scale and complexity of the problems.

Because the amount of time between laboratory solution of a problem, first prototype applications, and the widespread and easy availability of that solution is significant, the tables include a separate estimation of each. Projections for applications and availability are even rougher than the projection for a technical solution, since they depend on many social, economic, and market conditions.

These projections were compiled by analysis of existing sets of projections[51] and by interviews with technology experts. Projections of technological developments are inherently controversial, and experts do not always agree. Some experts will view these estimates as either too optimistic or too pessimistic. During the interviews with technology specialists, for example, several pointed out that some of the "key problems" listed in the table may

"See, for example, Manufacturing Studies Board, National Research Council, *Applications of Robotics and Artificial Intelligence to Reduce Risk and Improve Effectiveness: A Study for the United States Army* (Washington, D. C.: National Academy Press, 1983); R. E. Garrett and R. M. Mueller, "Strategic Analysis/Technology Trend Report, " Control Data Corp., May 15, 1981; D. Grossman and J. T. Schwartz, "The Next Generation of Robots, " in *Frontiers in Science and* Technology (Washington, D. C.: National Academy of Sciences, 1983, pp. 185-209.

Table 11.—CAD: Projections for Solution of Key Problems

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. High-resolution, color display of designs, with rapid generation of images[a]	A	●	■		
Both hardware and software:					
2. Low-cost, powerful microcomputer-based workstations for[b]					
a) electronics design	A	●			
b) mechanical design		A	●	■	
3. Independent CAD workstations linked by network, with access to super-computer for powerful analysis and simulation	A	●	■		
Software:					
4. Three-dimensional solid modeling systems, resulting in:[c]					
a) more realistic images	A		■		
b) enhanced ability to connect with manufacturing equipment	A		●	■	
5. Comprehensive, powerful computer-aided engineering systems[d] for mechanical design			A	●	■
6. Extensive design/manufacturing integration		A	●	■	

[a]While color displays are currently available, they tend to sacrifice either resolution (the fineness and clarity of the picture) or the speed with which the images can appear on the screen New techniques for displays, such as the use of dedicated microprocessor chips (sometimes termed "silicon engines") to generate images, promise to improve this situation.

[b]Microcomputer-based Workstations for CAD are now being marketed, but in the judgment of technical experts consulted by OTA, they are either not powerful enough and/or not inexpensive enough to be useful in a wide variety of applications

[c]CAD experts report that many systems for 3-D solid modeling are available now, but they are not being used because of their large appetite for computer Power, and because their capacity to link design data to manufacturing equipment is inadequate Part (b) of this entry refers to this ability to store and manipulate design data about the physical characteristics of a part in such a way that it can be transmitted to manufacturing equipment with only minimal intermediate steps

[d]This entry refers to modules powerful enough to allow extensive interactive testing, simulation and refinement of designs in a wide range of applications Such systems are strongly product-dependent, while they may be near available for certain products now (e g , integrated circuits, certain portions of aircraft and motor vehicles), they are much less advanced in other industries and applications

[e]This entry denotes the "window from design to production" which would, for Instance, allow designers to examine the production implications of design choices These Include the costs and necessary production processes, as well as the history of manufacturing similar items at the plant Such comprehensive connections would allow much more substantial Integration of CAD, CAM, and computer. based management

A solution in laboratories

● first commercial applications

■ solution widely and easily available (requiring minimal custom engineering for each application)

SOURCE OTA analysis and compilation of data from technology experts

never be solved at all-the development of standard languages for robots (table 12 item 10) for example, depends as much on market factors and political considerations among robot vendors and users as it does on technical issues. Similarly, development of artificial intelligencebased systems which could control much of a factory without human intervention (table 15, item 5) depends on fundamental advances in the field of artificial intelligence that are by no means assured.

On the other hand, it is possible that some of the advances in the accompanying tables may occur significantly faster than the tables indicate. This might be particularly likely if the Federal Government and/or industry were to choose to make dramatic increases in R&D funding for PA technologies. Chapter 8 discusses R&D funding in more detail.

However, industry observers report with virtual unanimity that the application of programmable automation in most industries is lagging significantly behind the technologies' development, and that there appear to be abundant, relatively easy opportunities for use of current automation technologies. Hence the main stumbling blocks in the near future for implementation of PA technologies are not technical, but rather are barriers of cost, organization of the factory, availability of ap-

Table 12.— Robotics: Projections for Solution of Key Problems

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Hardware:					
1. Lightweight, composite structures and new forms of drive mechanisms	A	●	■		
Both hardware and software:					
2. Force sensors	A s		■		
3. Versatile touch sensors		A	●	■	
4. Coordinated multiple arms		A	●	■	
5. Flexible, versatile grippers			A	● ■	
Software:					
6. Precise path planning, simulation and control with CAD	A		●	■	
7.3-D vision in structured environments which have been planned to simplify the vision task	A		■		
8.3-D vision in unstructured complex environments which have not been planned to simplify the vision task			A	●	■
9. Robust mobility in unstructured environments			A	●	■
10. Standards clarifying different versions of robot languages, and helping ensure a common language for similar applications. . . . . . , ...				■	

ò= Solution in laboratories
. = first commercial applications
solution widely and easily available (requiring minimal custom engineering for each application)

SOURCE OTA analysis and compilation of data from technology experts

Table 13.—NC Machine Tools: Projections for Solution of Key Problems

	Current (1984)	*1985-86*	*1987-90*	1991-2000	2001 and beyond
Hardware:					
1. Systems which can automatically and reliably remove a wide variety of metal chips produced in cutting[a]			A	● ■	
Both hardware and software:					
2. Reliable, widely applicable adaptive control to optimize speed of metal removal	A		●	■	
3. Tool wear sensors applicable to wide range of cutting tools	A	●		■	
4. Systems for measurement of parts of a variety of shapes and sizes while the parts are being machined		A	●	■	
Soft ware:					
5. Controllers to accommodate ties to robots	A	●		■	
6. Model-based machining in which the machine tool operates substantially automatically based on data about metal processes and the part to be produced		A	●		■
7, Widely applicable 3-D verification of NC programs using CAD-based simulations . .		A		●	■

[a]Systems currently exist for automatic removal of metal chips, but despite much Interest and research, they are neither very reliable nor generically applicable (i e , they can only be used for certain kinds of metals or cutting processes)
A = solution in laboratories
.= first commercial applications
■ = solution widely and easily available (requiring minimal custom engineering for each application)

SOURCE OTA analysis and compilation of data from technology experts

Table 14.—FMS: Projections for Solution of Key Problems

	Current (1984)	*1985-86*	1987-90	1991-2000	2001 and beyond
Hardware:					
1. Generic fixtures for holding a variety of work-in-process parts		A		● 9	
Both ***hardware and software:***					
2. FMS for:[a]					
a) cylindrical parts production	A 0			■	
b) sheet metal parts production	A ,			■	
c) 3-D mechanical assembly	A			● ■	
d) electronics assembly.	A .		■		
3. Materials handling systems which can handle a variety of parts in any sequence necessary	A o		■		
Software:					
4. Automatic diagnosis of breakdowns in the FMS.			A	●	■
5. Standardization of software interfaces between computerized devices in an FMS			A	●	■

[a]Almost all FMS currently running are used to machine t!c parts, (e g., engine blocks) which are those whose outer shape consists primarily of flat surfaces The projections in this entry refer to FMS for quite different applications: a) machining of cylindrical parts, such as rotors and driveshafts (or "parts of rotation, " in machining jargon, since they are generally made on lathes), b) stamping and bending of sheet metal parts, such as car body panels, c) assembly (as opposed to fabrication of individual parts) of three-dimensional products, such as motors, and d) assembly of electronic devices, such as circuit boards. While machines currently exist for automatic Insert Ion of electronic parts into circuit boards, an electronics FMS would integrate the insertion devices with soldering and testing equipment.
A – solution in laboratories
● = first commercial applications.
■ solution widely and easily available (requiring minimal custom engineering for each application)

SOURCE OTA analysis and compilation of data from technology experts

Table 15.—CIM: Projections for Solution of Key Problems

	Current (1984)	1985-86	1987-90	1991-2000	2001 and beyond
Software:					
1. Well-understood, widely applicable techniques for scheduling and logistics of complex materials handling systems that would allow full factory integration . .			A	●	■
2. Standard communication systems (networks)	A	●		■	
3. Standardization of interfaces between wide range of computerized devices in an integrated factory.			A	●	■
4. Data base management systems which could sort, maintain and update all data in a factory				▲ ●	■
5. Computerized factories which could run on a day-to-day basis with only a few humans in management, design functions					A

A = solution in laboratories.
● = first commercial applications
■ = solution widely and' easily available (requiring minimal custom engineering for each application).

SOURCE OTA analysis and compilation of data from technology experts propriate skills, and social effects of these technologies. These issues are more fully addressed in later chapters of this report.

Many in industry would argue that CIM is inevitably the future of manufacturing. Its advantages in cost, quality, flexibility, and control will, they assert, mandate its adoption. Many parts of computer-integrated manufacturing can be put together on an ad hoc basis now, and as the tables show, prototype solutions for many of the key problems already exist. However, several key aspects of the puzzle are as yet unsolved (the development of interface standards for computerized tools, in particular), and for CIM to be practical each of its elements must be mature, versatile, and relatively easily available commercially.

As noted earlier in this chapter, CIM does not necessarily imply manufacturing without humans. In fact, one of the biggest challenges on the road to CIM is learning to use humans in effective ways, to develop machines with which humans can work effectively, and to identify the points in the production process where maintaining human involvement may enhance flexibility, responsiveness, diagnostic power, and creativity. The extent to which that effective use of people in manufacturing will develop, and the extent to which CIM will remove humans from manufacturing environments, are still open questions.

Automation technology researchers report progress on virtually all of the technical problems, although the degree of progress often depends on research funding, commercial demand for related products, and inclinations of researchers. The technical barriers to increased sophistication in programmable automation are largely due to the complexity of the manufacturing environment, and to the fact that many manufacturing processes—e.g., machining, scheduling, design-have not been clearly understood in a way that can easily be computerized.

These projections of future technical capabilities, along with various other projections, imply that the remainder of the 1980's will be a time when applications will to some extent catch up with developed PA tools. Some technical improvements will doubtless be made during this time. But most prognosticators seem to see the 1990's as a period when the application of basic PA tools will become wide spread, and a number of major technical improvements will be available, particularly for robots and FMSs (see tables 12 and 14). While this may, in some cases, suggest that the 1990's seem far enough away to solve almost any technical problem, it also seems to indicate that the next decade will bring quite substantial increases in the power and potential uses of programmable automation.

Future Levels of Use of Programmable Automation

The rate of growth in use of programmable automation in the United States, known as the "diffusion" of the technologies, depends on factors both in the larger economy and at the level of individual firms and products. Some of the more general factors include availability of capital and skilled labor, international competition, and the amount of attention American firms devote to improvements in manufacturing processes. The last factor may be the most critical. Manufacturing engineering in the United States has been largely neglected both in engineering schools and in industry .52

Prompted in part by international competition, however, the mood among American industrialists (to the extent there is a "mood" in such a diverse group) seems to be changing. Increasingly, established management practices are being questioned in conferences and industry journals, and many industrial managers are closely examining improvements in manufacturing processes, particularly robots.* The extent to which this change

"See, for example, E. N. Berg, "Manufacturing's Academic Renaissance, " *The New York Times,* Oct. 30, 1983.

*Despite the generally rising interest in robotics, a significant group of people remain powerfully skeptical about the use of robots as one of the primary steps to enhance productivity. In a 1983 survey by the Institute of Industrial Engineers, for example, members of the society-who are closely involved with manufacturing processes on a day-today basis—rated robotics relatively low in effectiveness of a group of productivity-in mood will effect lasting and significant change in manufacturing, however, is uncertain. Many management specialists believe that such lasting change must include discarding powerfully entrenched habits in industry, particularly financially-oriented management strategies that discourage risk-taking and downplay quality relative to cost.[53]

In addition to these more general questions, a large number of factors come into play when an individual firm chooses to use or not to use programmable automation. Some of the technical factors include: the applicability of the technology to the problem at hand, which tends to vary according to the particular manufacturing processes used in each factory; the range of tasks to which a given tool can be applied; the cost of customization, particularly for new technologies where few standards exist and almost every application is a prototype; the ease of use of the tool; the reliability of the equipment; the compatibility of programmable automation with machines already in place; and finally, the capacity of different PA systems for upgrading and expansion.

Organizational factors can also have a significant effect on firms' automation decisions. For example, one researcher found that previous experience with automation was a key factor in successful applications,[54] and industry observers report that many unsuccessful attempts to use programmable automation have been due to premature jumps into complex systems. There can also be substantial resistance to change on the part of workers or management. Many manufacturers report, however, that production workers tend to accept technological changes such as automation, while strong resistance tends to come from middle managers who fear programmable automation will diminish their degree of control or eliminate their jobs.[55] Chapter 5 discusses organizational issues of PA implementation in more detail.

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enhancing methods. Only 29 percent had undertaken increased use of robotics in the past 5 years; 22 percent rated the step high in effectiveness, 48 percent moderate, and 26 percent low. Measures which received higher effectiveness ratings included capital investment for new or automated machinery generally, worker training, improvement of inventory control, and "systems innovations." The interpretation of these survey results could differ; some would argue that increased familiarity of industrial engineers with robotics will lead to higher perceptions of effectiveness. In addition, robotics was not viewed as unproductive by very many respondents; it simply appeared not to be the productivity tool of first choice. (See "Productivity Today: An Inside Report," The Institute of Industrial Engineers, Norcross, Ga.)

[53]See, for example, R. H. Hayes and W. J. Abernathy, "Managing our way to econonic decline," *Harvard Business Review,* July-August, 1980, pp. 67-77.

[54]J. Fleck, "The Adoption of Robots," *Proceedings of the 13th International) Symposium on Industrial Robots and Robots 7,* Apr. 17-21, 1983.

[55]OTA Automation Technology Workshop, May 29, 1983.