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Selected Aspects of Microelectronics Technology and Applications: Numerically Controlled Machine Tools*

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Summary

The trends of technological development in numerically controlled (NC) machine tools present certain difficulties for most developing countries. The technology focus has not only shifted to electronics from the traditional machine tool itself, where economies of scale are important, but the success is also dependent on system knowledge of the industries where NC machine tools are being used. Other ingredients in achieving success include the capability of global marketing where research, and development, and technical services are essential. The financial resources required for the various operations - in research, in production, in marketing - are also quite substantial.

The present document outlines the technological development which has led to increasingly complex systems. Today the NC machine tool is no longer a stand-alone machine but rather an integral building block in a very complex manufacturing process. The driving force behind technology development for NC machine tools may originally have been a desire to achieve high accuracy in machine parts. Although other considerations, such as flexibility to rapidly adjust to different customers or new market needs, have become much more important. Another essential factor is the desire to integrate all manufacturing stages from design to final processing which has become possible through the electronification of machine tools.

The cutting edge for the NC technological development today includes areas such as sensors and pattern recognition, communication protocols for using electronic data and systems analysis in order to achieve the desired integration. Thus, the success in modern machine tools appears to rest on the ability to mobilize substantial financial resources, to carry out advanced research and a keen understanding of market needs.

CONTENTS

INTRODUCTION

Numerically Controlled (NC) machine tools provide a good illustration of the pervasiness of IC technology in changing the traditional machine tools. The changes are not limited to the machine tools themselves - in which connection we are also discussing robots and sensors - but are also fundamentally affecting the manufacturing industry. Thus it is possible for an increasing number of producers to envisage fully automated factories where blue collar workers are almost non-existant. There can be little doubt that such changes, some of which have already taken place, have far reaching repercussions on both industrialized and developing countries. So, we argue that it is important to maintain a perspective which goes beyond the individual product categories in which technology change in itself is significant.

For the sake of reference it is worth remembering that the development and use of NC machine tools originated in the US aerospace industry in the early 1950s. This origin partly explains the differences in industrial structure for NC tools in the US and Japan to be briefly discussed later on.

Machine tools are power-driven (usually by electric motors) devices used mainly in metalworking for cutting and forming. The conventional machine tools are manually controlled or use cams and gears for automatic operation. The large metal-cutting machine tool sector has been subject to important technical change and international competition in recent years and the development of computer numerical control (CNC) is of major importance in this context. Numerically controlled (NC) machine tools are controlled by a programmable device. CNC machine tools are an advanced version using a microcomputer as the programmable device.

NC MACHINE TOOL PERSPECTIVES

In this section we will not only discuss NC machine tools but also robots and flexible manufacturing systems (FMS) which include both NC machine tools and robots. First, however, we will introduce selected statistics in order to provide a global perspective on NC machine tools. See Table 1.

Table 1
World machine tool production and trade, 1984 for selected countries (estimated in millions of US$)

	Production			Trade	
	Total	Cutting	Forming	Export	Import
Japan	4,474.6	3,709.6	765.0	1,741.0	181.8
FRG	2,803.8	1,971.2	832.6	1,967.7	456.8
USSR	2,953.4	2,296.1	657.3	235.7	1,390.1
USA	2,412.5	1,722.2	690.2	373.5	1,319.0
Italy	996.0	713.0	283.0	558.0	182.5
GDR	781.0a	608.6a	172.3a	725.1a	105.4a
Switzerland	714.8	663.8	51.1	672.0	130.4
France	465.5	376.2b	89.3b	250.1	301.2
PRC	494.4a	376.2a	118.2a	37.6a	140.3a
UK	376.9	313.6	63.3	278.6	339.5
Province of Taiwan	231.7	215.0	16.7	181.1	106.2
India	193.7	161.4	32.3	20.5	132.3
Republic of Korea	160.7	132.5	28.2	34.6	29.3
Brazil	103.6	87.4	16.2	27.7	39.3
Argentina	28.2	15.0	13.2	14.0	33.0
Singapore	20.8	19.3	1.5	57.4	138.5

a) Rough estimate from fragmentary data.
b) Estimated by NMTBA using totals from national trade associations and AM proportional metal cutting and metal forming shares.
Source: 1985-1986 Economic Handbook of the Machine Tool Industry. Virginia, NMTBA.

The total production of both cutting and forming machine tools amounted in 1984 to roughly US$ 20 billion, out of which cutting tools constituted the major share. See Table 1. Japan and the Federal Republic of Germany lead nowadays in the production of machine tools, if USSR is excluded, being followed by the USA. The People's Republic of China is reported to have a very sizeable production and this is also true for India. See again Table 7 for further details. The USA used to be the undisputed leader in the manufacture of machine tools but its share has been drastically reduced over the past couple of years. See Table 2.

Table 2

Production, exports and imports of machine tools, selected countries, 1981 to 1983 (millions of US$)

	Production			Exports			Imports		
Country	1981	1982	1983	1981	1982	1983	1981	1982	1983
France	809.4	564.8	560.0	390.4	295.0	295.2	566.5	479.3	351.1
India	184.6	182.9	184.0	17.1	18.2	21.5	86.6	153.9e	148.5e
Japan	4,796.9	3,796.4	3,541.1	1,692.9	1,272.5	1,263.6	215.7	220.4	171.3
Sweden	204.8	179.9e	156.6e	164.3	138.3	114.5	191.6	151.2	129.5
Switzerland	846.2	816.1	673.6	740.3	714.2	583.6	188.9	157.6	101.0
UK	720.7	607.7	398.8	577.7e	477.7	319.0	432.6	408.8	294.3
USA	5,131.0	3,745.0	2,132.7	949.0	574.0	359.1	1,432.0	1,218.0	921.1
FRG	3,953.1	3,505.0	3,193.5	2,584.9	2,206.4	1,950.4	616.4	488.6	452.7

e = estimate

Original source: International statistics on machine tools jointly prepared by CECIMO; IMTMA; JMTBA and NMTBA.

The availability of solid-state controls (the CNC systems) that turned the machine tool industry upside down, and the microprocessors, developed in the USA in 1972, have had a tremendous impact on the whole sector. Early CNC systems had incorporated minicomputers, but the microprocessor enabled increased reliability and reduced costs. Leading US suppliers were slow to accept solid-state technology, while the Japanese captured the large-volume-jobbing markets, first locally and later on in the USA and western Europe.

The following landmarks exemplify how the hardware technology in NC controls has changed dramatically over the years. At least seven generations of controller hardware can be identified:

1. Vacuum tubes (ca 1952)
2. Electromechanical relays (ca 1955)
3. Discrete semiconductor (ca 1960)
4. Integrated circuits (ca 1965)
5. Direct numerical control (ca 1968)
6. Computer numerical control (ca 1970)
7. Microprocessor and microcomputers (ca 1975)

Presently, technological innovation - of which IC technology, discussed earlier being only one example - seems to have no limits. Recent developments in various areas of industrial automation have created the necessary conditions for total, unmanned automation of manufacturing, servicing, etc. This points to the necessity of an integrated approach towards the introduction of robots and flexible automation. However, there exist significant technical, economic and social barriers to a broader application.

A major share of all machine tools are presently numerically controlled ones. This is evident from the figures, although of a fragmentary nature, which appear in Table 3.

Table 3

Investment in NC lathes as percentage of investment in all lathes in major producing countries

Year	France	FRG	Italy	Japan	Sweden	UK	USA
1974	n.a.	n.a.	n.a.	22	34	n.a.	n.a.
1975	n.a.	17	n.a.	23	43	n.a.	n.a.
1976	26	n.a.	15	28	42	19	n.a.
1977	47	n.a.	n.a.	43	53	21	n.a.
1978	n.a.	n.a.	n.a.	41	70	31	n.a.
1979	n.a.	n.a.	n.a.	52	70	38	n.a.
1980	52	47	50	49	69	47	57
1981	n.a.	n.a.	n.a.	45	78	73	n.a.
1982	68a	42	58	58	77	79	60
1983	78a	n.a.	n.a.	69	72	66	69
1984	85	59	n.a.	71	83	83	73

a) Export of conventional lathes exceeds production. Consumption of conventional lathes is therefore equal to imports.

Source: Jacobsson, Staffan: Electronics and industrial policy - the case of computer numerically controlled lathes. George Allen and Unwin 1986.

NC machine tools, the main focus of our discussion, cannot be generally utilized. In order to indicate the boundaries we will introduce four categories of production activity.

1. Continuous-flow processes
2. Mass production of discrete products
3. Batch production
4. Job shop production

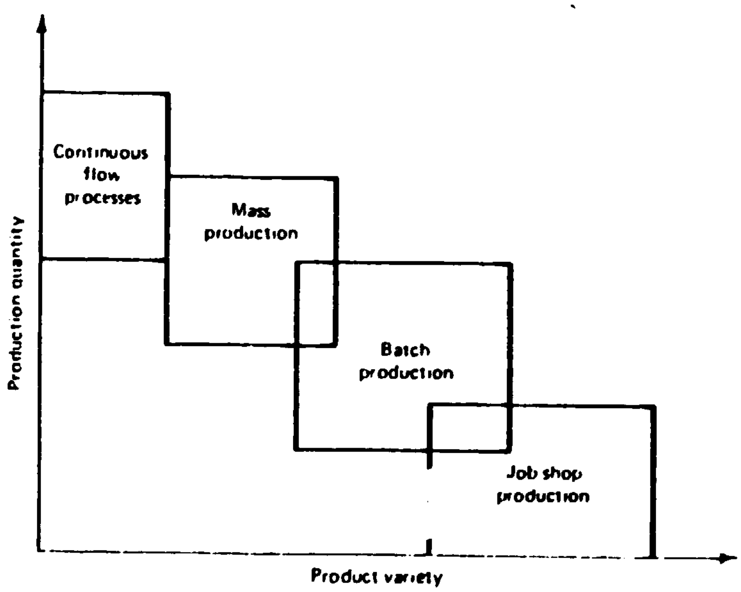
The definitions of the four categories are presented in Table 4. The relationships among the four types in terms of product variety and production quantities can be conceptualized as shown in Figure I. There is some overlapping of the categories as indicated in the figure. Table 10B lists some of the notable achievements in automation technology for each of the four production types.

Noteworthy in this context is the importance of computer technology in automation. Most of the automated production systems implemented today use computers. This connection between digital computer and manufacturing automation may seem perfectly logical to the reader nowadays. However, this logical connection has not always existed.

Many of the achievements in computer-aided design and manufacture have a common origin in numerical control (NC). The conceptual framework established during the development of numerical control is still undergoing further refinement and enhancement in today's CAD/CAM technology.

Figure I

Four production types related to quantity and product variations



Source: Groover, Mikell P & Emory W Zimmers, Jr; CAD/CAM: computer aided design and manufacturing. New Jersey: Prentice Hall, 1984.

Table 4
Four types of production

Category	Description
1. Continuous-flow processes	Continuous dedicated production of large amounts of bulk product. Examples include continuous chemical plants and oil refineries.
2. Mass production of discrete products	Dedicated production of large quantities of one product (with perhaps limited model variations). Examples include automobiles, applicances, and engine blocks.
3. Batch production	Production of medium lot sizes of the same product or component. The lots may be produced once or repeated periodically. Examples include books, clothing, and certain industrial machinery.
4. Job shop production	Production of low quantities, often one of a kind, of specialized products. The products are often customized and technologically complex. Examples include prototypes, aircraft, machine tools, and other equipment.

Source: Mikell P Groover & Emory W Zimmers Jr; CAD/CAM: computer aided design and manufacturing. New Jersey: Prentice Hall Int., 1984.

Table 5
Automation achievements for the four types of production

Category	Automation achievements
1. Continuous-flow processes	Flow process from beginning to end Sensor technology available to measure important process variables Use of sophisticated control and optimization strategies Fully computer-automated plants
2. Mass production of discrete products	Automated transfer machines Dial indexing machines Partially and fully automated assembly lines Industrial robots for spot welding, parts handling, machine loading, spray painting, etc. Automated materials handling systems Computer production monitoring
3. Batch production	Numerical control (NC), direct numerical control (DNC), computer numerical control (CNC) Adaptive control machining Robots for arc welding, parts handling, etc. Computer-integrated manufacturing systems
4. Job shop production	Numerical control, computer numerical control

Source: Mikell P Groover & Emory W Zimmers Jr; CAD/CAM: computer aided design and manufacturing. New Jersey: Prentice Hall Int., 1984.

Numerical control defined

Numerical control can be defined as a form of programmable automation in which the process is controlled by numbers, letters, and symbols. In NC, the numbers form a program of instructions designed for a particular workpart or job. When the job changes, the program of instructions is changed. This capability to change the program for each new job is what gives NC its flexibility. It is much easier to write new programs than to make major changes in the production equipment.

An operational numerical control system consists of the following three basic components:

1. Program of instructions
2. Controller unit, also called a machine control unit (MCU)
3. Machine tool or other controlled process

The program of instructions serves as the input to the controller unit, which in turn commands the machine tool or process to be controlled.

The controller unit consists of the electronics and hardware that read and interpret the program of instructions and convert it into the mechanical actions of the machine tool. The typical elements of a conventional NC controller unit include a tape reader, a data buffer, signal output channels to the machine tool, feedback channels from the machine tool and the sequence controls to coordinate the overall operation of the foregoing elements. Nearly all modern NC systems are sold with a microcomputer as the controller unit. This advanced type of NC is called computer numerical control (CNC).

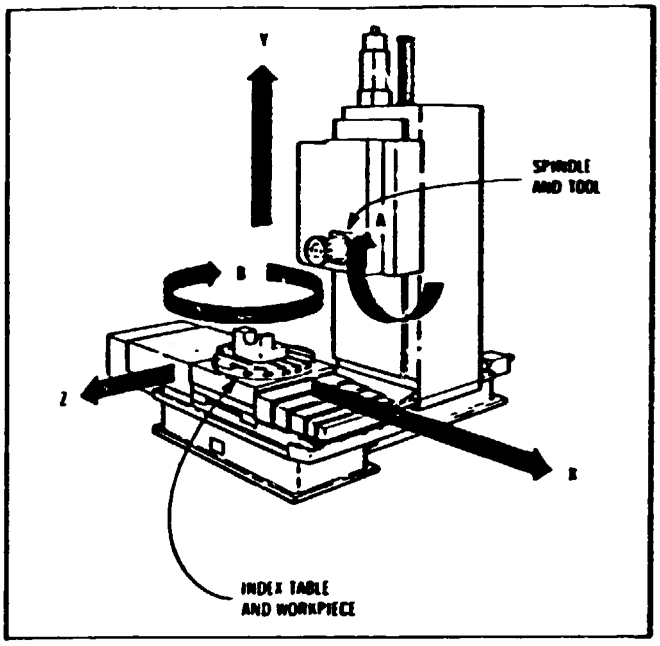
The third basic component of an NC system, the machine tool or other controlled process, is the part of the NC system which performs useful work. In the most common NC system, one designed to perform machining operations, the machine tool consists of the worktable and spindle as well as the motors and controls necessary to drive them. It also includes the cutting tools, work fixtures, and other auxiliary equipment needed in the machining operation.

NC machines range in complexity from simple tape-controller drill presses to highly sophisticated and versatile machining centers.

We will now clarify the various levels of electronification of machine tools, from the traditional machine to a flexible manufacturing system involving several computer numerical controlled machine tools.

The simplest configuration is a 5-axis workstation as illustrated in Figure II. All settings are done manually and controlled by a person who must be highly skilled.

Figure II

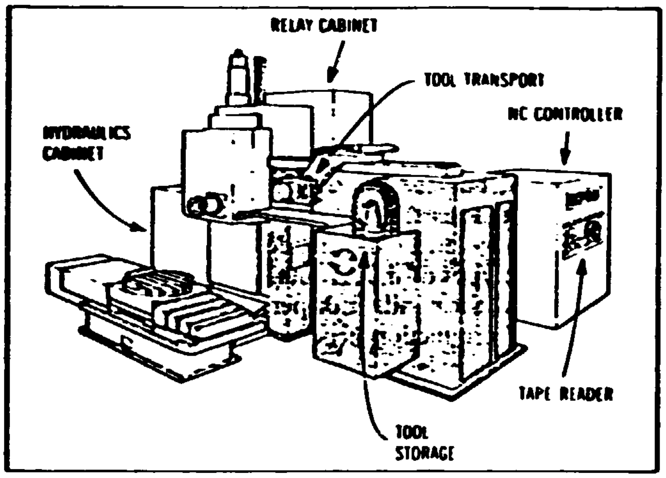


On a typical 5-axis workstation, the spindle and tool move in three orthogonal directions (X, Y, and Z) relative to the part. In addition, the table rotates in the B axis and the spindle head rotates about the A or horizontal axis. The tool, therefore, can contact the workpiece from the top or side or from an angle; the workpiece need not be refixtured except to approach the bottom.

Source: Computer Design April 21, 1983, p. 134.

The next stage of development includes the numerical control and the automatic tool changers. See Figure III.

Figure III

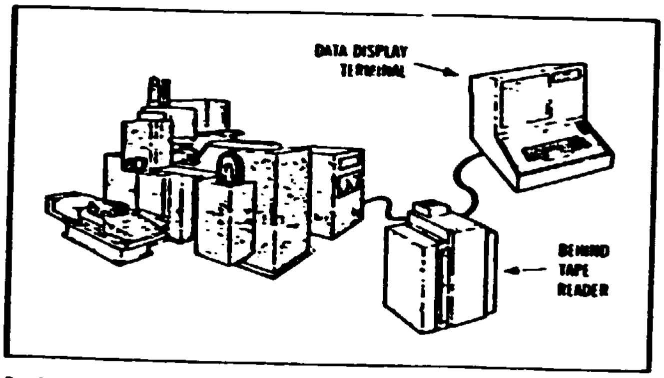


Adding numerical control, tape reader, and automatic tool changer to the 5-axis workstation relieves the operator of many time-consuming tasks. The NC controller provides automated axis control as well as tool changing in a sequence set up by a punch paper tape.

Source: Computer Design April 21, 1983, p. 134

By adding a computer setup (behind tape reader and data display) the NC machine tool is converted into a computer numerically controlled (CNC) system. See Figure IV.

Figure IV

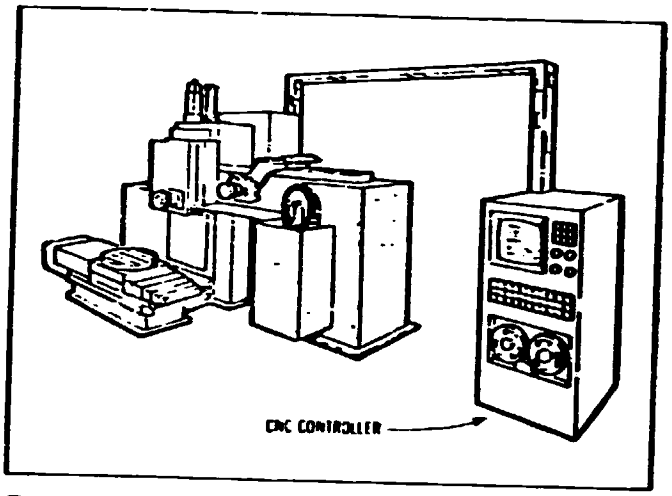


Including a behind tape reader (BTR) and a data display terminal converts the NC workstation to a computer numerically controlled (CNC) system. The BTR retains part programs from several tapes; the operator chooses one of those programs through the terminal for instruction to the controller.

Source: Computer Design, April 21, 1983, p. 134.

In more recent systems the various electronic subsystems are combined into a single unit and the operations of the machine tool are now fully controlled by a minicomputer or a microcomputer. See Figure V.

Figure V

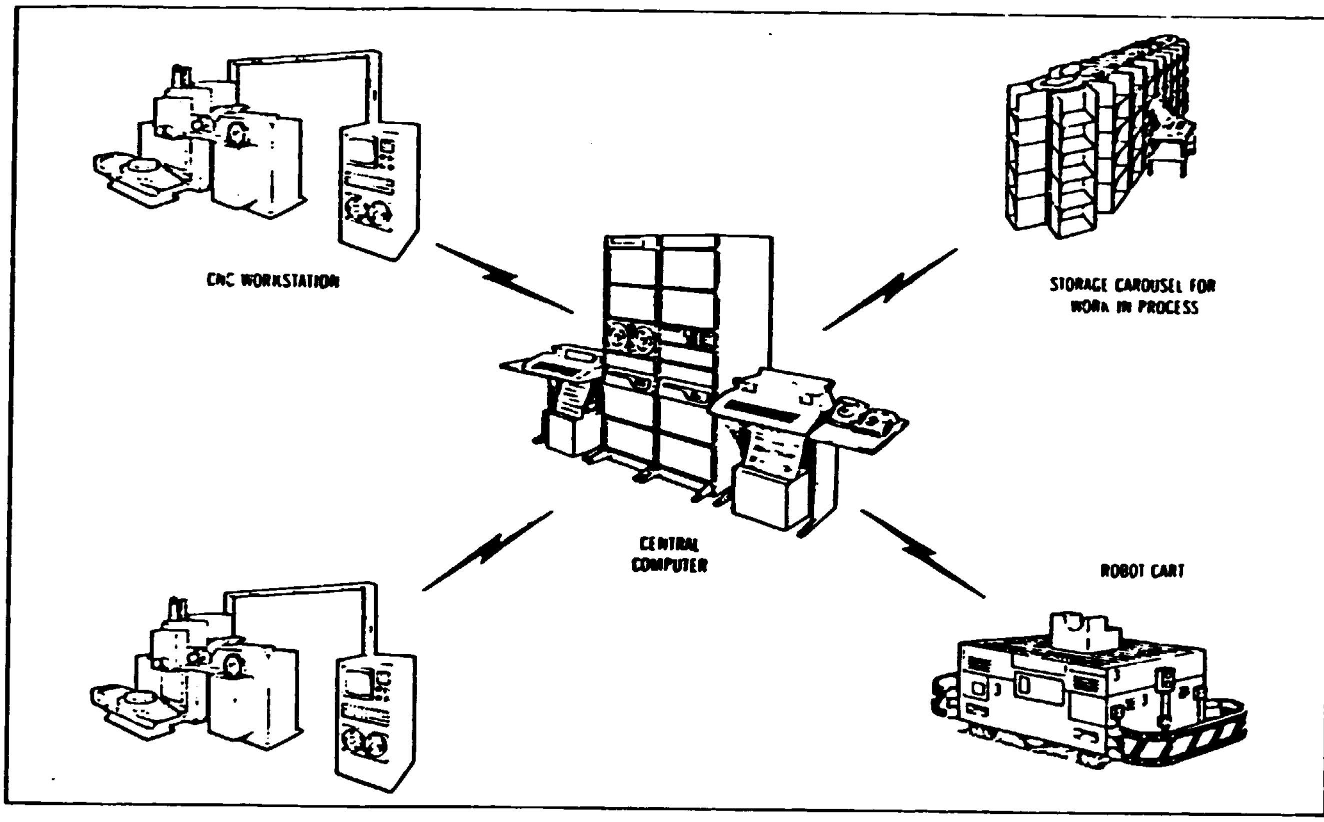


Functions of the NC controller and BTR are combined in more recent CNC systems. Either a minicomputer or, now, a microcomputer provides the control.

Source: Computer Design, April 21, 1983, p. 134.

At a still higher level of electronification, several CNC workstations can be combined with robots, robot cars and automatic storage systems, all of which are, in principle, controlled or supported by a central computer. See Figure VI.

Figure VI



A central computer can manage several CNC workstations as well as other components such as a robot cart or storage carousel in a direct numerical control (DNC) configuration. Part programs are maintained in a central library.

Source: Computer Design, April 21, 1983, p. 134.

In a study carried out by the Technical Change Center in London, the authors reach the conclusion that formal R&D does not play a major role in the machine tool companies studied, including those in Japan. In most cases, only 1 or 2% of sales was devoted to formal R&D. If product development activities and special "task forces" to work on product problems are included, the figure is generally about twice as great.

The authors further note that of the firms in the study, only the Japanese firms and the two Swiss firms allocated any formal R&D effort to what the authors call "production-engineering design and development", by which they mean the development of improved manufacturing techniques for the production of machine tools.[1]

However, there can be little doubt that the emergence of NC and CNC machine tools have been driven by major R&D efforts. The development of microprocessors, programs (software) and sensors as well as efforts to drastically change both products and production processes are very important incentives in this context.

It is often noted that VLSI circuits provide a focal point for a new strength in the industrial process and manufacturing control market as well as the consumer market, much in the same way the automobile did over 50 years ago.

Automatic control has already experienced considerable change due to VLSI microprocessor products that have been developed for other consumer and communication applications. With the tremendous increase in capital spending for factory automation, the IC makers appear to have increased their endeavours to produce special products for control.

We will now return to a more detailed discussion of the basic approaches in NC machine tools. A common categorization includes the following three:

1. Computer numerical control (CNC)
2. Direct numerical control (DNC)
3. Adaptive control

CNC involves the replacement of the conventional hard-wired NC controller unit by a small mini- or microcomputer. By programs stored in its read/write memory, the small computer is used to perform some or all of the basic NC functions. One of the characteristic features of CNC is that one computer is used to control one machine tool. This differs from the second type of computer control, direct numerical control, which involves the use of a larger computer to control a number of separate NC machine tools.

The third control topic, adaptive control, does not require a digital computer for implementation. An AC system measures one or more process variables, such as cutting force, temperature, horsepower etc. and manipulates feed and/or speed in order to compensate for undesirable changes in the process variables. Its objective is to optimize the machining process, something that NC alone is unable to accomplish. Many of the initial adaptive control projects relied on analog controls rather than digital computers, but modern systems employ microprocessor technology.

Advances in computer technology have continued to provide smaller digital control devices with greater speed and capacity at lower cost. This has permitted the machine tool builders to design the CNC control panel as an integral part of the machine tool rather than as a separate stand-alone cabinet. Subsequently, floor space requirements for the machine can be reduced. The use of VLSI circuits in these controllers is of further benefit for both the machine tool designer and the machine user. Fewer components in the controller makes it easier and less expensive for the machine tool builder to fabricate. Fewer circuit boards, which are readily replaced, reduce the burden on the user for maintenance and repair.

The external appearance of a CNC machine is very similar to that of a conventional NC machine. Part programs are initially entered in a similar manner. Punched tape readers are still the common device to input the part program into the system. However, with conventional numerical control, the punched tape is cycled through the reader for every workpiece in the batch. With CNC, the program is entered once and then stored in the computer memory. Thus the tape reader is used only for the original loading of the part program and data. Compared to regular NC, CNC offers additional flexibility and computational capability. New system options can be incorporated into the CNC controller simply by reprogramming the unit. Due to this reprogramming capacity, both in terms of part programs and system control options, CNC is often referred to by the term "soft-wired" NC.

However, controller functions are not necessarily implemented in software - the Japanese have even developed a single large scale integration chip for interpolation and servo control. The designer must evaluate such features and perhaps provide the option (to the part programmer) of bypassing them. For example, the user may wish to program a special interpolation scheme rather than use those available.

Adaptive control (AC) machining originated out of research in the early 1960s sponsored by the US Air Force at the Bendix Research Laboratories. The initial adaptive control systems were based on analog control devices, representing the state of technology at that time. Presently, AC uses microprocessor-based controls and it is typically integrated with an existing CNC system.

In machining operation, adaptive control means a control system that measures certain output process variables and uses them to control speed and/or feed. Some of the process variables that have been used in adaptive control machining systems include spindle deflection or force, torque, cutting termperature, vibration amplitude, and horsepower. In other words, nearly all the metal-cutting variables that can be measured have been tried in experimental adaptive control systems. The motivation for developing an adaptive machining system lies in trying to operate the process more efficiently. The typical measures of performance in machining have been metal removal rate and cost per volume of metal removed.

Just as CNC had certain advantages over a conventional NC system, there are also advantages associated with the use of direct numerical control (DNC). However, the DNC systems that were marketed in the late 1960s and early 1970s were extremely expensive. Their high cost, combined with an unfavourable economic climate at that time, caused business managers to resist the temptation to plunge into the new DNC technology. Also, the DNC systems available at that time were somewhat rigid in terms of management reporting formats and hardware requirements.

The development of CNC systems, together with lower cost computers and improvements in software, have resulted in the development of hierarchical computer systems in manufacturing. In these hierarchical systems, CNC computers have direct control over the production machines and report to satellite minicomputers, which in turn report to other computers. This hierarchical approach is advantageous compared to the DNC packages offered earlier during the 1970s. The main advantage is higher flexibility. The information system can be tailored for the specific needs and desires of the user. This is much better than the early DNC systems, in which the reporting formats were fixed, which could sometimes result in an overflow of data being provided to management. In the same way, in some cases details that management needed could be ommitted.

Another advantage of the hierarchy approach is the ability to gradually build the system instead of implementing the entire DNC configuration all at once. This piece-by-piece installation of the computer-integrated manufacturing system is a more versatile and economic approach. It permits changes and corrections to be made more easily as the system is being built. It also allows the company to spread the cost of the system over a longer period of time and to obtain benefits from each subsystem as it is installed. The hierarchical computer arrangement embraces the DNC philosphy, which is to provide useful reports on production operations to management in real time. One might say that DNC has not really been replaced by this new approach; it has simply altered its physical form. This evolution in the configuration of DNC and its inclusion of computer numerical control have resulted in the introduction of the term "distributed numerical control" for the initials DNC.

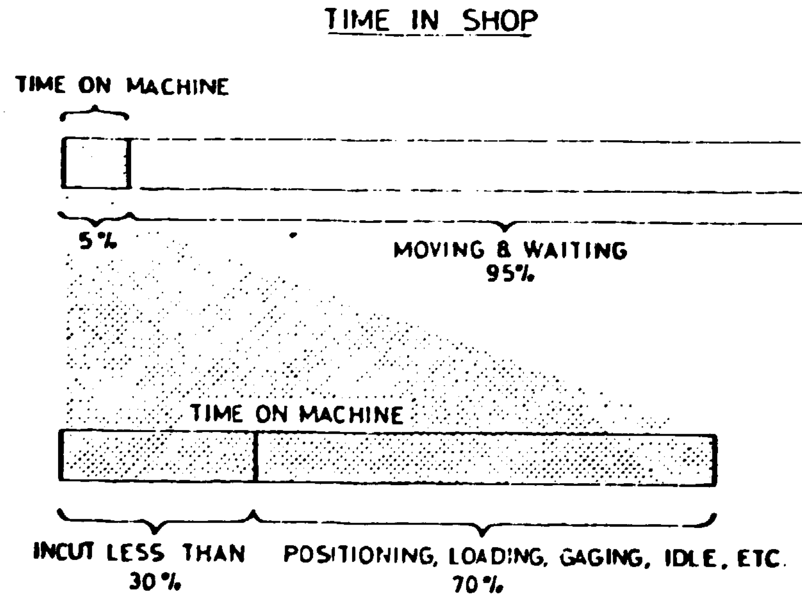
Flexible manufacturing systems (FMS)

One of the important developments in DNC was the introduction of the flexible manufacturing system. An FMS is a group of NC machines (or other automated workstations) which are interconnected by a materials handling system. All of the machines and the work handling system are controlled by computer. Flexible manufacturing systems were first introduced around 1970. Owing to the very high cost of the systems (several million dollars per FMS), there were only about a dozen systems installed by the end of 1980. However, FMS offer such a high potential for productivity improvement in batch manufacturing that the number of installations is expected to grow substantially during the 1980s. FMS represents an important step in the evolution of the computer-automated factory of the future.

The application of computer technology has a great potential for cost-reduction in discrete part manufacturing. This is shown in Figure VII.

Figure VII

Life of the average workpiece in the average (batch-type production) shop



Source: Advances in CAD/CAM. Edited by TMR Ellis and OI Semenkov. Amsterdam: North-Holland, 1983.

The time average work-piece in batch-type metal cutting production shops stays only about 5% of its time in machine tools, and of that 5%, only about 30% (or 1.5% of the overall time) is actually spent as productive time in removing metal.

There are two main areas where the greatest improvement in the economy and productivity of discrete part manufacturing can be made. First, reduction of time of parts in process in the shop, and thus of the resulting extremely high inventory of unfinished parts on the shop floor, and of finished parts waiting for others in process so that assembly of the product can proceed. Results already obtained with prototype computer integrated machining systems show that they have the potential to increase time on the machine to as high as 90%. The amount of idle capital which such an improvement could free up would be enormous.

Indeed, there is a major economic force encouraging rapid computer integration of manufacturing and the eventual development and implementation of computer integrated factories.

The second area of potentially great improvement is that of percent machine utilization. The 30% time in cut must be combined with the fact that the average machine spends approximately 50% of its time waiting for parts to work on (because of the 95% time in transit). As a result, the average machine tool in a batch-type shop is being utilized productively (i.e. is actually cutting metal) only about 15% of the time. Again, results already obtained with prototype computer integrated machining systems show that they have the potential to increase machine utilization to as high as 90%. The increased utilization of capital, the reduction in labour and overhead costs as well as the increases of productivity which such an improvement could bring about are of great significance. Obviously this represents another major economic force encouraging rapid computer integration of manufacturing and the eventual development and implementation of computer integrated factories.

The choice of configuration depends to a large extent on the type range and batch size of parts being handled by the FMS.[2] One of the major splits so far has been into prismatic' - that is parts based around cuboid shapes such as gearboxes - and 'rotational' parts such as axles and shafts. The former are suitable for machining on advanced CNC machining centres whilst the latter depend on lathes and cylindrical grinding equipment; the majority of FMS installations are for prismatic types, reflecting the difficulties in handling rotational parts and their relatively lower value. No FMS is yet able to handle both prismatic and rotational parts, but this is clearly a direction in which future flexible systems will have to move. It is understood that Japanese companies have already shown some activity in the area.

Most prismatic parts systems make use of pallet-based handling. Conveyors are used to move pallets containing light weight components and those with short machining cycle times, whilst automated guided vehicles are used to transport heavier components. Since AGVs are slower than conveyors, efforts have been made to develop suitable fixtures to enable one pallet to carry several different components. This would mean a longer cycle time at the machines and compensate for the speed disadvantage. One answer to this problem is the adoption of cube fixturing which allows several components with short machining times to be attached to a cube. When this is then palletised and presented to the machine tool, machine utilization is rapidly increased. One company which had adopted this system, intended eventually to produce in excess of 500 different parts on a one-off basis, and assemble these parts as they came off the FMS, reducing WIP to virtually nil.

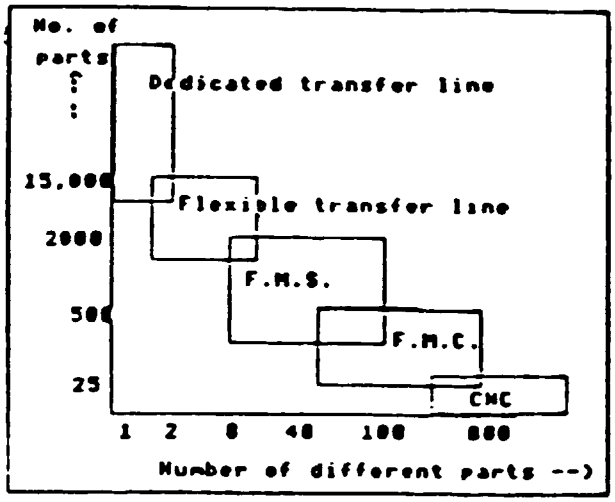
Most prismatic systems employ automatic pallet changers and other transfer machinery; many use pallet systems for tool management as well, often employing a tool-changing robot at the machine tool. All FMS in use have some form of automatic tool change and many have head changing ability on machine tools as well.

Experience with rotational FMS is less developed but here the handling is usually based on conveyors and robot transfer to and from machine tools.

For these, and other reasons, users of FMS need to pay careful attention to identifying exactly which parts will go down the FMS. In turn this must be related to the value of the parts involved and how much it presently costs to produce them. Currently the aim appears to be to go for large, heavy high cost components. It is here that the principles of Group Technology have become widely applied, with a growing emphasis on collecting together 'families' of parts which require similar machining operations.

The result, in terms of systems configuration, of this emphasis on parts is that a range of solutions have been developed. These run from systems which are designed to handle high volumes but with some variety and which might more appropriately be called 'flexible transfer lines' (FTL), through what might be termed "classical" FMS with a medium mix of volume and variety, right down to low volume, high variety applications which are being termed 'flexible manufacturing cells' (FMC). Figure VIII illustrates this differentiation.

Figure VIII
Options in flexible manufacturing technology



Source: John Bessant & Bill Haywood; The introduction of flexible manufacturing systgems as an example of computer integrated manufacturing. Brighton Polytechnic, 1985.

Robots

The existence and further development of NC machine tool is significant in itself. So is the emergence of intelligent robots since the mid 1970s. However, it is the combination of NC machine tools, intelligent robots and various other electronically controlled devices which provides a new setting for many types of integrated industrial production.

In terms of control technology and programming, industrial robots share much in common with numerical control machines. Robots are used for moving workparts and tools in the performance of industrial tasks. An important number of these tasks are concerned with the loading and unloading of production machines, including NC machines. The robot and the machine form an automatic work cell, with raw workparts being fed into the cell by conveyor and completed parts leaving the cell by conveyor. All this is accomplished with little or no human attention.

Robots are key elements in flexible manufacturing systems which will be briefly discussed after some general comments on control.

Discrete-part manufacturing equipment is increasingly being described initially by how it is controlled rather than by the function it performs. Examples of this are widespread: CNC-controlled multi-axis machining centers, computer-directed flexible manufacturing cells, programmable controller instructed automatic palletizers, computer-controlled injection molding machines, etc. Part of this trend is a promotion ploy in this age of the automatic factory, but more importantly it represents a fundamental change in how manufacturing equipment is designed and how it is purchased.

In the past machinery was initially mechanically designed and then, as kind of an afterthought, the control system was hung on as best it could be. But his approach no longer suffices with the complex automatic machinery of today.

It is becoming increasingly evident that the availability of the microprocessor is offering a unique opportunity to ingenious designers of industrial control equipment. This applies to all types of instrumentation and control components including programmable controllers, process controllers, data acquisition systems, sensors, programmable motion controllers.

The industrial robot is a key component in a total CAM system. The long term aim is 'full computer integration'. This means developing compatible software for both CAD and CAM. It also means that truly flexible, programmable automation would be available for the manufacture of dissimilar workpieces produced in small batches.

An industrial robot consists of three elements - manipulator, controller and power unit. The manipulator is a mechanical structure of joints and linkages which can be moved in various axes. A wrist and gripper can be added to the manipulator to make further movement possible. One important measure of a robot's versatility is the number of axes (degrees of freedom) which are under control.

The controller can be as modest as a simple pneumatic logic system or as sophisticated as a mini-computer. Simple, non-servo robots operate against mechanical stops and limit switches. The advanced servo-controlled devices employ feedback instrumentation which tells the controller when the robot gripper has reached the desired point in space.

The power unit can be pneumatic, hydraulic or electrical. Pneumatic drives are used mainly for simple, non-servo robots. Their speed and positional accuracy are difficult to control but they have the advantage of reliability and low cost. Hydraulic drives make use of compact motors and cylinders which generate high power levels. Positional accuracy and repeatability are both susceptible to fine control. Electrical drives are generally used for high accuracy applications involving light loads. They drive stepper motors, servo-motors and solenoids to produce highly sophisticated control capability.

It seems clear that the limitations today are in the areas of system design capability, process knowhow, and economic justification and are not a function of control equipment availability to satisfy application requirements. Provided the knowhow and money are there the control equipment is on the market to permit process and manufacturing plants to accomplish just about anything they want to achieve in terms of advanced automation.

Robots have become in recent years a reality for users in many countries. The application of robots provides already a practical way of solving problems of labour productivity, increasing quantity and speed of mass production, meeting higher qualitative demands, replacing humans in dangerous work etc. This situation is found, though, almost solely in industrialized countries. The availability of sophisticated miniaturized and relatively cheap hardware, due to the development of microelectronics, is the most important factor influencing the wide diffusion of robots. Serious technical problems, however, remain to be solved, such as the need for

- continuous innovation of robot mechanisms to permit higher operational speed, manipulation of heavier loads, increased accuracy, reliability and safetey, easy maintenance, etc.;

- design and production of suitable vision, tacticle, acoustic and other sensors located on or close to the robot's end effectors; and
- rapid development of appropriate software tools, both standardized packages for universal tasks and interface with the whole system.

The close links between producer and users of robots will become increasingly important as production and manufacture of many products will undergo major changes. The further development of robots and their increasing availability at lower costs are likely to have a major impact on assembly operations as well as product design which can be summarized in four major categories.

First, electronics will become more important both in the manufacture process and in the products to be manufactured. Second, the joining of various components within a product will be modified and simplified in order to accomodate the robots. Third, the number of parts in a product will continue to decrease. Fourth, the design of a product will increasingly become automated with an closer link between design and manufacture.

The total stock of industrial (programmable) robots had at the end of 1984 reached almost 100,000 according to recent research.[3] Japan has a very large share with about 64,000 units followed by the USA with 13,000. Sweden has an impressing figure of 1,900 and West Germany 6,600 robots. It must be stressed that this survey includes only programmable robots while other statistics, mainly emanating from Japan, include all types of simpler devices which have automatic functions.

The Japanese classification has five categories
1) a slave manipulator teleoperated by a human master;

2) a limited-sequence manipulator (further classified into "hard-to-adjust" and "easy-to-adjust" categories);
3) a teach-replay robot;
4) a computer controlled robot;
5) an intelligent robot.

It is only the last one which is usually referred to as robot.

Table 4
World robot population

Country	no. robots Dec. 1984	working population x 1000	no. robots per 10,000 workers
Japan	64,000	20,000	32.0
Sweden	2,400	1,350	17.7
Belgium	859	1,350	6.4
Germany,Fed.Rep.of	6,600	11,500	5.7
UK	2,623	5,500	4.8
France	3,380	7,700	4.3
USA	13,000	30,000	4.3
Spain	518	1,350	3.8
Italy	2,700	7,800	3.5

Source: Steady growth for robots in 1984. The Industrial Robot, March 1985, p. 30.

The table above shows that so far, the introduction of robots has had very little impact on the overall employment situation.

The industrial structure is characterized by a large number of companies and it has been estimated that in 1983 there were some 250 in Japan (including 80 which produced robots for their own use only), approximately 50 in the USA and probably the same number each in western and eastern Europe. The number of firms on a world-wide basis with external robot sales can thus be estimated to be about 300.

There can be little doubt that in the future the manufacture of robots will be concentrated to a relatively small number of producers which are handling the mass market. The reasons are manifold. First, the technological change is rapid and the manufacture of robots requires considerable R&D resources to stay competitive. Second, there are considerable economies of scale to be reaped in production as well as development and marketing. The application work required from the customers is very knowledge-intensive and cannot easily be mastered by small companies. So, even if small companies may maintain their niches, the rapidly growing market for robots may in the future be captured by a small number of companies.

Almost all applications have until quite recently been found in a couple of sectors, mainly the automobilc and electric machinery industry. In light of this it is not surprising to find that a number of the large automobile manufacturers like Volkswagen, Renault, Fiat and BMW in Europe and General Motors in the USA have started their own manufacture of robots. The major uses for new industrial robots are spot-welding, painting and machine tending, which a few years ago covered almost 75% of all new industrial robots. It is noteworthy that assembly robots hardly existed in 1980 but they were expected to capture 14% of the market in 1985.

The reason for this is the following. Many manufacturing processes have over the past two decades become automated.

In the future, very high investments will be required in order to achieve further improvements. At the same time, technical measures like assembly robots, have become available to automate small batch production and attention is increasingly turning to parts handling, assembly and robots technology.

The robot industry is a high-technology industry which in some respects differs from other comparable high-technology industries such as microelectronics and telecommunications industries. These differences stem mainly from the fact that the development of robotics, to a higher degree than that of the above-mentioned areas, is based on the integration of a multitude of technologies from a variety of industries - machine tools, computers, process control, sensor technology and software, as well as various kinds of application knowledge in welding, painting, assembly etc. [4]

The robot industry is a very young one. The first commercial use of industrial robots - as they are now commonly defined - dates back to the beginning of the 1960s. However, it was not until the middle of the 1970s that ouptut reached a level which warranted the consideration of the industrial robot industry as a separate entity. Before that time, only very few companies were achieving yearly sales in the order of as much as 10 million dollars; orders were received only intermittently from a very thin customer base.

For several reasons, the inception of the industrial-robot industry can be said to date back to the middle of the 1970s:

(a) The results of the R&D work carried out in the period 1960-1975 began to be ready for commercialization;

(b) New microelectronic components became available, especially the microprocessors (developed during the early 1970s) which form the basis of today's powerful and cost-effective control systems;

(c) Time is required for potential users to assess the technology and acquire the necessary knowledge for its use. Not until the middle of the 1970s did the large automotive, electrical and electronics manufacturers commence planning long-term and large investments in robots.

Since the second half of the 1970s, the robot industry has seen very rapid growth. In terms of value, as well as of units, average yearly growth of robotics has exceeded 30%, attracting the entry into the business of both new and large established firms. According to several forecasts, the high growth rate of robot installations is likely to continue, at least throughout the present decade. See Table 4 for information on present stock of robots.

Application areas

Industrial robots have been applied to a great variety of production tasks. For purposes of organization, we will divide the applications into the following seven categories:

1. Material transfer
2. Machine loading
3. Welding
4. Spray coating
5. Processing operaticns
6. Assembly
7. Inspection

The use of robots has initially been concentrated to a limited number of tasks of which welding and spray-coating within the automobile industry have been prominent. In order to realize the full potential of robots we will below provide a list of incentives which indicate a much higher intensity of robot use. Before doing so, however, we will refer to an OECD survey which indicates that the high growth rates which the robot industry has experienced in the past is expected to continue. See Table 5.

Table 5
Expected diffusion of robots in selected countries
(no. of robots)

Country	1981	1985	1990	1981-85 %	1985-90 %
Japan	9,500	27,000	67,000	30	20
USA	4,500	15,000	56,000	35	30
Sweden	1,700	4,100	8,300	25	15
FRG	2,300	8,800	27,000	40	25
UK	713	2,700	10,000	40	30
France	790	2,100	6,500	28	25

Source: OECD Industrial Robots Their Role in Manufacturing Industry.

Incentives for intelligent robot development

Let us examine the incentives for the development of intelligent robots.

(A) Social incentives: The most important incentive for developing robots should be social - replacing humans, who perform undesired jobs, by machi... s. Japan, for example, is planning to embark upon a large-scale program for the development of robots operating in hazardous environments. The ranking of robot development should thus be ordered according to job undesirability, i.e. jobs that are:

1) lethal - e.g. in a high radiation environment;
2) harmful - e.g. paint spraying, handling toxic chemicals;
3) hazardous - e.g. combat, fire fighting;
4) strenuous - e.g. lifting heavy loads, visual inspection;
5) noisy - e.g. forging, riveting;
6) dull - e.g. sorting, assembling.

(B) Technoeconomic incentives: The second most important incentive for robot development is reducing the manufacturing cost of products and improving their quality.

1) Current limitations: in spite of the strong social and economic incentives mentioned above, only a very small fraction of the entire human work force in the world has been replaced by industrial robots. Furthermore, it is estimated that the growth rate of the total number of industrial robots (excluding teleoperators and limited-sequence manipulators) will rise from 2,000 per year in 1980 to 40,000 per year in 1990; these figures correspond to a yearly replacement of about 0.003-0.006% of the total blue collar work force in the industrialized countries. Such a low rate of growth of robot population has resulted primarily from the limitations of today's industrial robots.

2) Future capabilities: the best way to overcome the limitations of today's "muscle-only" robots is to provide them with intelligence, i.e. adaptive sensing and thinking capabilities. Such intelligent robots will be able to compete more effectively with not only blue-collar workers but also white-collar workers. Most industrial companies have not yet agreed with this observation but they will agree

hopefully not too late, when the threat of worldwide market competition becomes unbearable.

(C) Socioeconomic problems: Development of intelligent robots may raise many problems, the major one of which is national unemployment. Obstruction of the development of intelligent robots by the labour unions will only worsen the unemployment problem because other countries, especially Japan, will proceed with such development and, as a result, foreign competition will become stronger.

Technical approach [4]

The technical approach to intelligent robot development should be based on application of artificial intelligence (AI) techniques to robotics under four engineering constraints:

1) high reliability - the robot must be robust; if it fails, it should be able to detect the error and recover from it or call for help;

2) high speed - the robot should be able to perform its functions as fast as necessary;

3) programmability - the robot should be flexible (able to perform a class of different functions for a variety of tasks), easily trainable (for new tasks or modification of old ones), and intelligent (able to perceive problems and solve them);

4) low cost - the cost of the robot should be low enough to justify its application.

Clearly, these constraints may conflict with each other. For example, increasing the robot speed or lowering its cost may also lower its reliability. A trade-off, therefore, must be engineered for different applications according to the significance of each constraint.

Research and Development

As shown above, a robot system may be divided into effectors, sensors, computers, and auxiliary equipment. Robotics R&D topics associated with these major functional components include manipulation (of arms), end-effectors, and mobility; sensing (in general), noncontact sensing, and contact sensing; adaptive control (which utilizes sensors to monitor and guide effector actions); robot programming languages and manufacturing process planning (which generate task specific computer programs that are executed by the top level and lower level controllers).

From the technological point of view, the development of industrial robots is moving towards:

- A rapidly increasing degree of sophistication, especially with respect to control system and sensors (e.g. machine vision); and
- The integration of industrial robots with other computer-controlled manufacturing equipment. This will require extensive development work in the area of systems control, interface and communication.

To retain its position in the technological forefront, a company must make very heavy investments in R&D. In the USA it has been estimated that in 1982 the total sum spent on R&D by the American robot manufacturers amounted to $26.5

million, or 19% of the value of total shipments. Few other industries are likely to have such a high degree of R&D intensity.

The decision of a manufacturer when making his selection amongst the above-mentioned strategies is generally dependent upon his financial, technological and manpower resources as well as on the existence of international subsidiaries of the parent company for marketing purposes. Within this framework each strategy is evaluated with respect to:

- investment costs: R&D, capital investment and marketing;
- market size and market growth; and
- competition.

Investment cost is a very heavy item in the cost picture of a robot manufacturer, especially if all three elements listed above are included. One would therefore be tempted to conclude that the obvious strategy oto select is the manufacture of general-purpose robots intended for a multitude of applications requires extensive investment in process knowledge and the development of peripherals and accessories for each type of application. Thus, the economies of scale that might be achievable with respect to the basic robot unit might therefore be lost owing to the increased costs of the development of each process application. This can of course be offset if the manufacturer has the capability of effecting large-scale production for each application area, a situation likely to occur only if the manufacturer has a strong international market.

In view of the above, the production of general-purpose robots will probably be mostly confined to large manufacturers with international outlets whilst smaller and medium-sized independent manufacturers will mainly concentrate on the manufacture of either special-purpose or value-added robot systems.

Owing, on the one hand, to the fact that the robot industry is an emerging industry having strategic importance for the development of total industry and, on the other, to ghe large size of the necessary R&D investments, most European Governments have set up specific R&D programmes for robot development.

The investment for sales and service organization and marketing, is extremely costly, especially if it is undertaken ona wide international basis. Only the very large robot manufacturers have financial and manpower resources to engage in such investment. Smaller and medium-sized firms are therefore usually obliged to concentrate either on regional markets and/or joint-venture or licensing agreements with foreign firms.

Finally we will provide a few comments which indicate the future role of robots in more integrated flexible manufacturing systems.

Robots are often key constituents of FMS. They can be interfaced with CNC machine tools in a machine cell, where their task is to load and unload workpieces. In more ambitious applications, robots can figure in full blown FMS layouts under DNC, where a master computer - which may be located remote from the factory - passes instructions to robots, conveyor system and CNC machine tools. In this type of application, the possibilities for unmanned manufacture of small batches of varying workpieces becomes economically feasible.[5]

Sensors

The further introduction and diffusion of NC machine tools depends more on further development on programs (software) and conceptual changes of the production process, than any development, per se, of the NC machine tool. However, there is little doubt that various types of sensors may facilitate and enable more efficient and more closely integrated production processes, in particular when robots are to be utilized.

Sensors are key elements of control systems since they give the information about the state of the process. Sensors are more important for robots than for the other NC machine tools discussed earlier.

The development of sensors for measuring composition and product quality has resulted in considerable progress, in the past few years. There has also been considerable development of sampling techniques. Because of its innovative character, it is difficult to predict the development of future sensors. Developments should, however, be watched closely because availability of new sensors will invariably lead to new possibilities for automation.

Engineers have always tried to design sensors to be as selective as possible in their sensitivity and to produce a nice, tidy linear output. This can mean choosing an unsatisfactory type of sensor, or trying to clean up the signal in a central processor. For example, engineers prefer to install theremocouples rather than semiconductor thermostors to measure changes in temperature. The thermocouple is awkward and less sensitive, but it produces a linear output. The new approach, which still has to make the transition from laboraotry to industry, involves putting a processor on the sensor.

There is constant debate about whether a robot should have tactile sensing or vision sensing, or maybe both. Vision is good for parts identification and acquisition, whereas tactile techniques are better for parts insertion. So robots can use both types of sensing.

With the moves to increase automation of factories, development of robots, especially intelligent robots, has drawn keen interest from industry. Control systems and mechanical technologies have led to advanced robot capabilities. But for taking robots to a more advanced step in which they can move on the basis of the work to be done and the environment of the workplace, rather than simply following preprogrammed instructions, sensors will be indispensable. Visual sensors are among the most important for more advanced robots.

With visual sensors, recognition decisions are performed in a preprocessing unit that draws the essential information from image data obtained by using a camera to form the basis for a decision within predetermined parameters. On the basis of these parameters, the main processor makes the final determination and the controller drives the movement of the system.

Visual recognition systems take over from human in three basic functions, viz, discrimination, position and orientation detection, and inspection.

The basic components of a machine vision system are the following. The sensor, most commonly a television camera, acquires an image of the object that is to be recognized or inspected. The digitizer converts this image into an array of numbers, representing the brightness values of the image at a grid of points; the numbers in the array are called pixels. The pixel array is input to the processor, a general-purpose or custom-built computer that analyzes the data and makes the necessary decisions (identifying the object, detecting flaws). The processor may also have some degree of control over the sensor, the object, or the environment; it may, for example, be able to focus or adjust the gain on the sensor, slow down the movement of the object past the sensor, or vary the illumination.

Recognition systems of various degrees of sophistication have been developed by a very large number of firms. Many of the basic 2-D vision techniques have been incorporated into such systems. The major limitation on these systems is computation time.

Machine vision has not yet achieved the power and flexibility of human vision, but it is improving continuously and can already perform very well in various restricted environments. As the cost of computer power continues to drop, the range of practical applications of machine vision will continue to expand.

One area to watch is all types of applications which require extremely high measurement sensitivites. Fibre-optics sensors are already setting some new levels in measurement sensitivities. The posibilities to replace complex mechanical and electronic sensor devices with little more than a piece of glass or silica is not only attractive, but may solve many applications problems.

When determining the appropriate monitoring concept, several considerations must be taken into account, such as the required data for the monitoring function and how it should be recorded and processed. The monitoring strategy will determine the solution with regards to the parameters and the sensor principles.

The task is the collection and transfer of encoded information and signals from one place to another. Wire cabling performs this task by means of its conduction of electronic voltages and currents; fibreoptics conveys this basically electronic information in the form of optical signals - light modulated in amplitude, phase, frequency, or polarisation. Bundles of glass, silica, or plastic fibres can also transmit entire images with little loss of capacity.

All fibre-optic sensors can be classified into one of two classes according to their mode of operation;

* **Extrinsic sensors**:
In such sensors, the fibre itself is passive, and is used only to transmit light from one location to another, e.g. from a light source to the sensing location and/or from the sensing location to a detector. The fibre plays no role in the actual sensing itself; sensing results from non-fibre related effects, such as reflected or scattered light, interruption of a light beam, etc. Any influence of the fibre itself on such sensing is undesirable and will lead to inaccurate sensor response.

* **Intrinsic sensors**:
In this case, the fibre itself is the active element, and propagation of light through the fibre is used not only for signal transmission, but for quantifying the parameter to be measured. The phenomenon to be measured or parameter to be quantified must influence fibre characteristics in some way so that the light flux transmitted by the fibre will be altered from the quiescent case. The received signal must be related to the measured quantity in some unambiguous way.

These two basic sensor types may be combined to form hybrid sensor devices and systems for the simultaneous measurement of two or more external parameters by a single sensor head.

EXPERIENCE IN DEVELOPING A CAPABILITY IN NC MACHINE TOOLS

A small number of developing countries including India and China, and several NICs have ventured into the development of NC machine tools. The Republic of Korea and the Province of Taiwan prove to be quite successful cases, partly learning lessons from Japan. However, we will use the experience of Argentina as a more relevant case to highlight the problems facing a developing country.

The present decade is characterized by the rapid diffusion of microelectronics in industry. This will lead to increases in labour productivity and to significant changes in the structure/organization of jobs. The linkage of mechanics with electronics is sometimes called "mechatronics". It deals with the appalication of advanced technologies, such as microelectronics, to achieve greater efficiency in the design, production and operation of machinery. Robotics is believed to be the leading mechatronic principle. Robotics seems to be a typical example of the natural convergence of automatic control and information technology in the field of factory automation. We will now describe this change in a few developing countries and we will start by looking at the Argentinian case.

NC machine tools (NCMTs) constitute the automated machine-building technology that has received the widest diffusion in Argentina during the last decade. The technology is in use not only in large firms producing oil equipment, nuclear equipment, ships and heavy electrical equipment, but also in medium and some small firms producing agricultural machinery, pumps, valves and auto parts. However, it is estimated that less than 100 establishments are employing this technology.

The diffusion of automated machine-building technologies in Argentina took first place in the late 1970s, when the economy was characterized by a bias in government policies against the manufacturing industry through overvaluation of the peso.[6] This made imported goods relatively cheap and wages, in dollar terms, far higher than what might be regarded as "normal" in a semi-industrialized country. In a study commissioned by UNCTAD, the author presents the following hypothesis: at first, the main reason for introducing NCMTs was linked to the need to replace skilled labour in the context of industrial rationalization in order to be able to compete with imported goods. However, once the above-mentioned economic situation ended in early 1981, as a result of a reversal of the economic policies carried out since 1978, another situation prevailed in which domestic firms would have little incentive to introduce this technology.

The motivations of the Argentinian user firms for introducing NC machine tools do not seem to concur with what is found in the industrialized countries. In spite of the special characteristics of the Argentinian economy at the time of introduction of the technology, NCMTs continued to be installed afterwards in a situaiton of relatively low wages and this indicates that capital-labour substitution has not been the main reason for the adoption of the technology, as is the case in the industrialized countries. Large users fabricating complex equipment, acquired NCMTs for technological reasons. The product to be manufactured makes the use of this technology almost imperative. In this context it is important to note that in these cases the technology is introduced not in a rationalization context but in connection with changes in the product mix to include more complex items. For smaller users, reduced labour costs have been achieved via shorter machining times, and in this way some capital-labour substitution may take place, though not with the intensity seen in the industrialized countries.

When analysing the diffusion of NCMTs, local production of these devices cannot be overlooked. Proximity to the supplier and the reputation of the indigenous producer in the domestic market are factors that have facilitated the purchase of this equipment by medium and small firms. Despite the small scale of production and given the fact that key component items such as the electronic control unit are imported, prices of locally made lathes are not very much higher than imported lathes.

The pioneer firm in this field has entered into the manufacture of more advanced lathes and machining centres under licensing agreements and a newcomer has emerged with NC equipment of its own design. This indicates that Argentina's production of NCMTs is gaining momentum. Given the critical situation of the balance of payments because of the debt burden, it is clear that imports of NCMTs will be more restricted than in the recent past, making domestic production of this equipment a profitable venture. In view of this fact, the degree of protection to be given to domestic producers, the duration of such protection and the extent of domestic participation (including regarding electronic components) are key issues on which policy decisions have to be taken. In other words, the difficult question that needs to be answered is to what extent and for how long user industries, and the economy as a whole, should pay the costs of strengthening domestic production in this critical branch. If the tariff protection and the degree of local participation remain at the current level, another important issue is to what extent this domestic effort is a step in the right direction for the creation of an internationally competitive industry.

Regarding CAD, although some diffusion has already taken place in Argentina a few large firms, the high cost of the technology and its relative underdevelopment have prevented a more significant diffusion. The experience of the user firms seems to be rather encouraging with respect to the technical advantages of the technology. However, the economic justification for using CAD/CAM for drafting and design is rather dubious in a country with low wages, unless other benefits can compensate for this situation.

It is nevertheless likely that CAD/CAM will continue to be diffused in the future, and there is some scope for indigenous production of software. The possibility of using some cheap CAD/CAM systems for programming NC machine tools should be explored because this is an area in which the domestic market will certainly become significant.

Robot technology, which basically replaces unskilled workers in repetivite operations, is being introduced in Argentina, though in a very limited manner, in metalworking industry. This in spite of very low wages of unskilled labour and the high level of unemployment in the country in recent years.

The introduction of the automotive producers is linked to the transnational character of the parent firms to which the Argentine subsidiaries belong. Another important factor is the commitment of these TNCs to use robot technology not only in the industrialized countries but also in the semi-industrialized countries, even in those countries where no significant export operatiosn are envisaged. The way in which TNCs have been proceeding in this field clearly shows that the technological logic of the design and production process of new car models prevails over the economic conditions of the host country. This reduces the room for manoeuvre of the host countries in obtaining better technological and economic conditions in TNC operations. In the Argentine case, this situation has been aggravated by the complete freedom with which the companies have been developing their technological activities and the poor export performance of the automotive industry.

A different aspect is that a leading new technology is introduced into a country not for reasons linked to labour costs but with regard to consistency of product quality and the improvement of working conditions. This clearly leads to the possibility of indigenous developments in this field. The efforts made by Argentine metalworking companies and by the French motor car company, though having a different rationale, are an indication that there is room for the development of a technology policy in this area. Under the present economic conditions, robots should receive less priority than NC machine tools and CAD/CAM.

We will now turn our attention to robots by mentioning the recent development in the Republic of Korea. To stimulate development of automation equipment, the Korean government has sponsored two projects for robot development; one is being carried out by Daewoo Heavy Industries (DHI), and the other by Samsung Precision Industries (SPI). These commmpanies are members of two of the biggest groups in Korea, which have annual sales in the region of US$ 5-7 billion. It is noteworthy that the Koreans leave the work to industry, whereas the Taiwanese for example, carried out the original development in government laboratories.

It is generally agreed that DHI is leading the other Korean comapnies towards the production of general-purpose robots, but when it comes to actual installations, Hyundai Machine has produced a number of spot welding robots which are already in use at Hundai Motors' newly extended plant at Ulsan. Production on the new line started in January 1985, and sales of the new Pony car started two months later.

To develop a wider range of robots, the Hyundai group has meanwhile set up a consortium, including the shipbuilding, engineering and electronics companies. Hyundai Machine will be the manufacturing unit. Hyundai Electronics Industries is currently deciding whether it should develop its own robot controller and CNC, or find a licensor.

Gold Star Tele-Electric produced an educational robot, similar to that developed by Mitsubishi Electric for some time, but owing to lack of interest, production has ceased. Gold Star Tele-Electric also produced five manipulators for withdrawing mouldings from injection moulding machines. These are used in-house, but at present there are no plans to produce this type of robot on a larger scale. The company has started a feasibility project for an assembly robot, but the company experts do not expect there to be any market for robots in Korea until the 1990s. This view is echoed by Samsung Precision Industries. The main explanation for this situation is that local labour costs are approximately US$ 3/hour including large fringe benefits.

Thus the Republic of Korea is not likely to be a fruitful market for robots for another five years or so. However, by that time, the main industries in the country will have developed a range of prototypes, and will be in a good position to dominate their home market.

The entrance fee for entering into robots has become quite high. It is currently estimated that approximately 100 manyears are required by any robot manufacturer in the industrialized countries in order to develop a robot up to the prototype stage. This amounts to roughly US$ 10 million and does not include any marketing costs. By using existing components and drawing on the earlier designs it may be possible to reduce this amount by about 50% for a major modification of an existing robot model.

As discussed earlier, there are two prerequisites - which are to a considerable degree contradictory - for achieving success in the robot business. On the one hand, there is the need for heavy R&D investment, which in turn provides incentives for internationalization in order to achieve a larger production volume over which the R&D cost ana be distributed. On the other hand, as internationalization requires large investment in marketing and the establishment of service and installation organizations, it might justify concentration on certain regions or certain market segments.

There is, however, a third approach, which most robot manufacturers have adopted: the achievement of economies of scale through partnerships, joint ventures or licensing agreements with various companies on different markets. For the licensor the advantage lies in the fact that his R&D costs will be partly reimbursed without his needing to invest in foreign market organizations (provided of course that the licensee is successful). The licensee has at the same time the advantage of not having to invest in R&D for robot development and is able to concentrate on value-added activities and marketing.

From reading robot news in the Japanese economic press in the early 1980s, the impression was created that the robot manufacturers are increasingly drawn into a close of relations of joint development, joint manufacture and joint marketing. However, this was at the time partly an illusion due to false reporting but mainly due to a preoccupation of many manufacturers in Japan to establish internaitonal outlets for their products. The reason was that many of them are small or very simple and most of them lack the proper distribution channels for robots. Today the situation is quite different with a few powerful robot consortia been recently formed. The most important is the partnership between General Motors in the USA and Fanuc in Japan. However, the robot manufacturing sector includes a fairly substantial number of small companies which cooperate in a complex network of supplier links.

Some general conclusions regarding the importance of international cooperation in the robot area can be drawn from current experience:

(a) Most licence agreements are drawn up between west Europe or Japanese manufacturers (licensors) and American manufacturers (licensees). At the same time, several west and at least one east European manufacturers have purchased licensing rights from Japanese manufacturers. There are some examples of licensing agreements signed in he direction opposite to that described above.

(b) Only the more important robot manufacturers, affiliated to large international enterprises, have established international sales subsidiaries.

(c) Amongst this group of robot manufacturers, only a few have established foreign robot manufacturing subsidiaries. In this context the major companies are the following: [7]

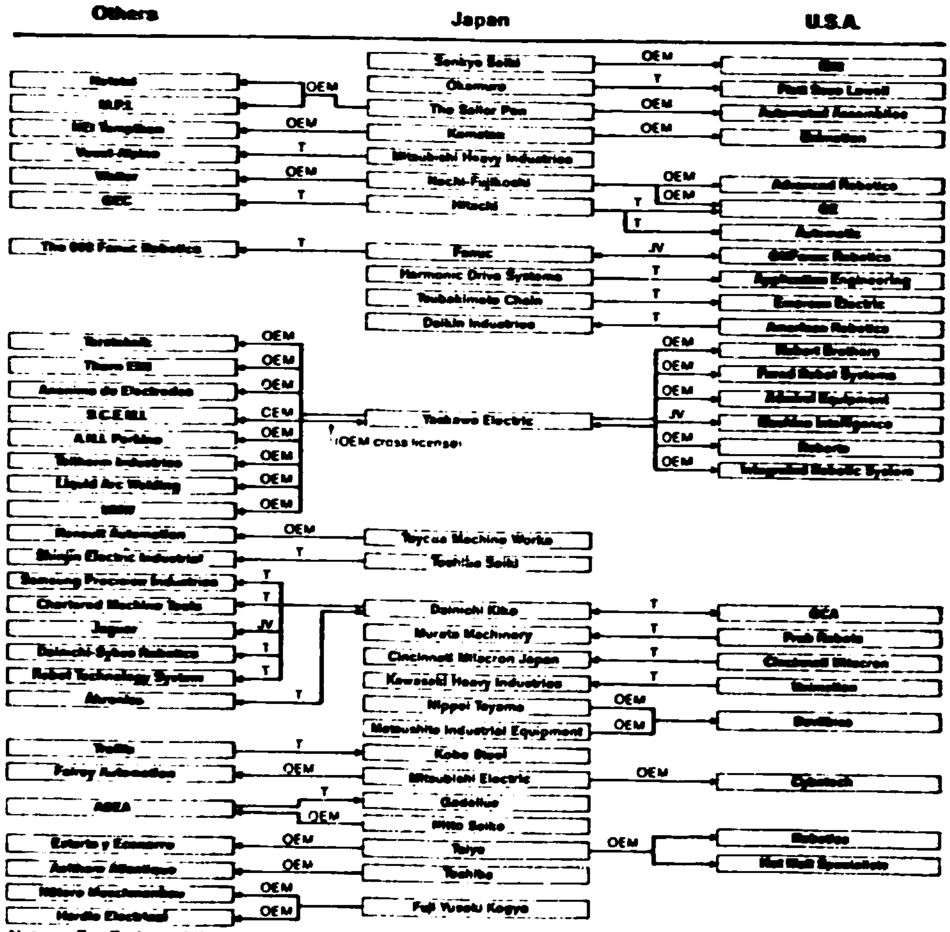
Robot Manufacturer	Manufacturing subsidiaries in:
ASEA	USA, France, Spain and Japan
Unimation (Westinghouse)	UK
Fujitsu Fanuc	USA (joint venture with General Motors)
Cincinnati Milacron	UK

(d) Besides undertaking some direct export sales, most of the medium- and smaller-sized robot manufacturers export either through joint ventures or sales/manufacturing licensing agreements with foreign firms. The cost of establishing sales and service subsidiaries on international markets are seldom justified for this group of manufacturers, taking into account both the strong competition and the low sales volume. When discussing trade in the robot industry, it is necessary to consider not only the volume of direct sales but also the transfer of royalty payments derived from licensing agreements. There is a very dense network of joint ventures and licensing agreements amongst the world's robot manufacturers. See Figure IX.

Figure IX

International industrial cooperation on robots

(As of April 1985)



Notes T = Technical tie-up JV = Joint venture
OEM = Original-equipment manufacturing
Arrows indicate the flow of products and technologies

Source Japan Industrial Robot Association

Source. Journal of Japanese Trade & Industry, 1985 no. 4, p 37

POLICY ISSUES

The characteristics of the market and an ability to understand that situation is critical for formulating and implementing technology policies and company technology strategies.

We will finally refer to the conclusions of an analysis of the demand structure and the technological change.[8] The author, Mr Franco Malerba, states that the effects of the structure of demand on the rate and direction of technological change have characterized not only the semiconductor industry but also several other industries. These effects have been particularly relevant in the specialized equipment supplier industries, such as machine tools and CAD. Malerba takes as an example the case of the electronics-based NC machine tool industry, where Japanese firms focused their innovative efforts on this technology for the domestic automobile industry, while American firms focused their innovative efforts for the domestic aerospace industry. The consequence was that the Japanese industry innovated in small, low-cost NC machine tools while the American industry innovated in larger and more expensive NC machine tools. In the case of CAD industry, the military aerospace demand in the USA affected the rate and direction of technological change and the international competitiveness of domestic firms differently than civilian demand in Europe.

There are significant effects of the changes and diversities in demand structures on the rate and direction of technological change which point to the importance of the linkages and interdependencies among sectors in the study of technological change. Malerba says that if an industry is a specialized supplier or a science-based industry, changes and differences in the structure of demand will reflect the evolution of various user industries over time and across countries. It is important to note that such an evolution may affect the rate and direction of technological change in the specialized supplier or science-based industry through a wide range of channels.

Malerba stresses that it is essential to understand the effects of the structure of demand on technology change since it is of a different type than the demand-pull effect. While the demand-pull and technology-push terms refer to factors that affect the rates of technological change across sectors and over time, the structure of demand refers to a factor that affects the rate and direction of technological change within a single sector, given certain sectoral technological opportunity conditions.

Malerba concludes that when attempting to influence the rate and the direction of technological change in a specialized supplier or science-based industry, public policy should not only act on the supply side but should also pay attention to the demand side and eventually use public procurement or intervene in user industries. Policies on the supply side which try to replicate successful policies adopted in the past or chosen by other countries, may prove unsuccessful if the structure of demand is different.

However, it is important to understand the linkages between demand structure and industrial structure to be created. In this respect some of the NICs show a very different picture from that of India and we will conclude by referring to a presentation made by C Edquist and S Jacobsson.[9]

In reply to the question raised as to why certain countries have made phenomenal progress in the field of electronics it was suggested that the fundamental difference between objectives and the industrial framework, governing the development of industry in general, must be recognized. It was stressed that the objectives, philosophies and the industrial framework "are largely determined by the size, security, environment, communication needs, economic structure and factor endowments, technological strategy and educational resources of each country".[9]

It was implied that -art of the differences in performance can be explained by the fact that the objectives are different in India compared withthe other countries. The DoE report states: [9] "We have adopted a strategy for development of the electronics industry which seeks:
- to maximise the enormous resource which our huge domestic market constitutes;
- to ensure indigenous production of as much as possible of electronic equipment for our strategic defence, communication, space and atomic energy needs;
- to achieve technological self-reliance (not in terms of shutting out foreign technology, but in inducting it where necessary and then adapting and developing it appropriately while meeting the technological needs of our strategic electronic products maximally indigenously) to use the technological and industrial capacity built to meet domestic needs, as the spring-board for our exports".[11]

In sum, we would like to stress that no country can succeed in developing a capability in technology intensive products if it overlooks the role of the market Some developing countries have such huge market that they provide a potential resource for domestic developing or inviting foreign companies to bring their technology into partnership with indigenous entrepreneurs. Other export-oriented countries may opt for alternative approaches basing themselves on external markets.

Now, we will indicate a more fundamental concern about developing an indigenous technological capability in high technology sectors. For many developing countries, and in many sectors, it may be more essential to develop a capability to use advanced technology, rather than to establish a capability to manufacture products which embody or are based on the most advanced technology. The earlier descriptions of trends in the manufacture of NC machine tools clearly show the very considerable barriers which exist for entering into this technological field. At the same time, it has become evident that developing countries cannot remain outside this technological revolution. This is clearly illustrated in machine tool manufacturing which provides an interesting example of the impact of new technologies on the economies of scale. UNIDO notes in a report from 1984 that prior to the introduction of NC, many machine tools were relatively standard items.[10] Markets could be thus won by price and cost reductions resulting from large-scale production. As the new technologies developed, however, the value-added per item became significantly greater so that smaller-scale production could be profitable. On the other hand, R&D costs have risen rapidly, yielding scale economies to those businesses which could spread their overheads over large production runs.

The UNIDO study also argues that in a number of sectors or subsectors, the optimal scale of production has been expected to be shifted downwards. This would open up wider possibilities for industrial production in developing countries, aiming in the first place at the domestic market. the reasons for this are manifold. New technologies, such as CAD or robotics affect a large range of industrial sectors. Branch specific technological breakthroughs have taken place in sectors such as iron and steel, fertilizers and segments of pulp- and food-processing industries. It is expected that similar breakthroughs can take place in the petrochemical and textile industries. In sectors such as agricultural machinery, building materials and bicycle manufacturing, small scale solutions than can be promoted and applied are available as alternative to traditional technologies.

The changing economies of scale for various industrial sectors are not yet well understood. However, technological development, particularly in electronics, microprocessors and computer-based support, has drastically pushed the level of optimal scale downwards in some sectors. Other technological trends, e.g. in the areas of iron and steel and fertilizer production, have introduced a new dimension to the scale problems in those sectors. Similar breakthroughs may be expected in other sectors. The obvious problem for developing countries is to participate in and get access to this technological development. This can only be gained by getting access to the advanced technology from the outside. The linked size of market and the lack of a dynamic change in most markets as well as the technological and financial barriers, clearly indicate that a gradual approach will be necessary for most countries.

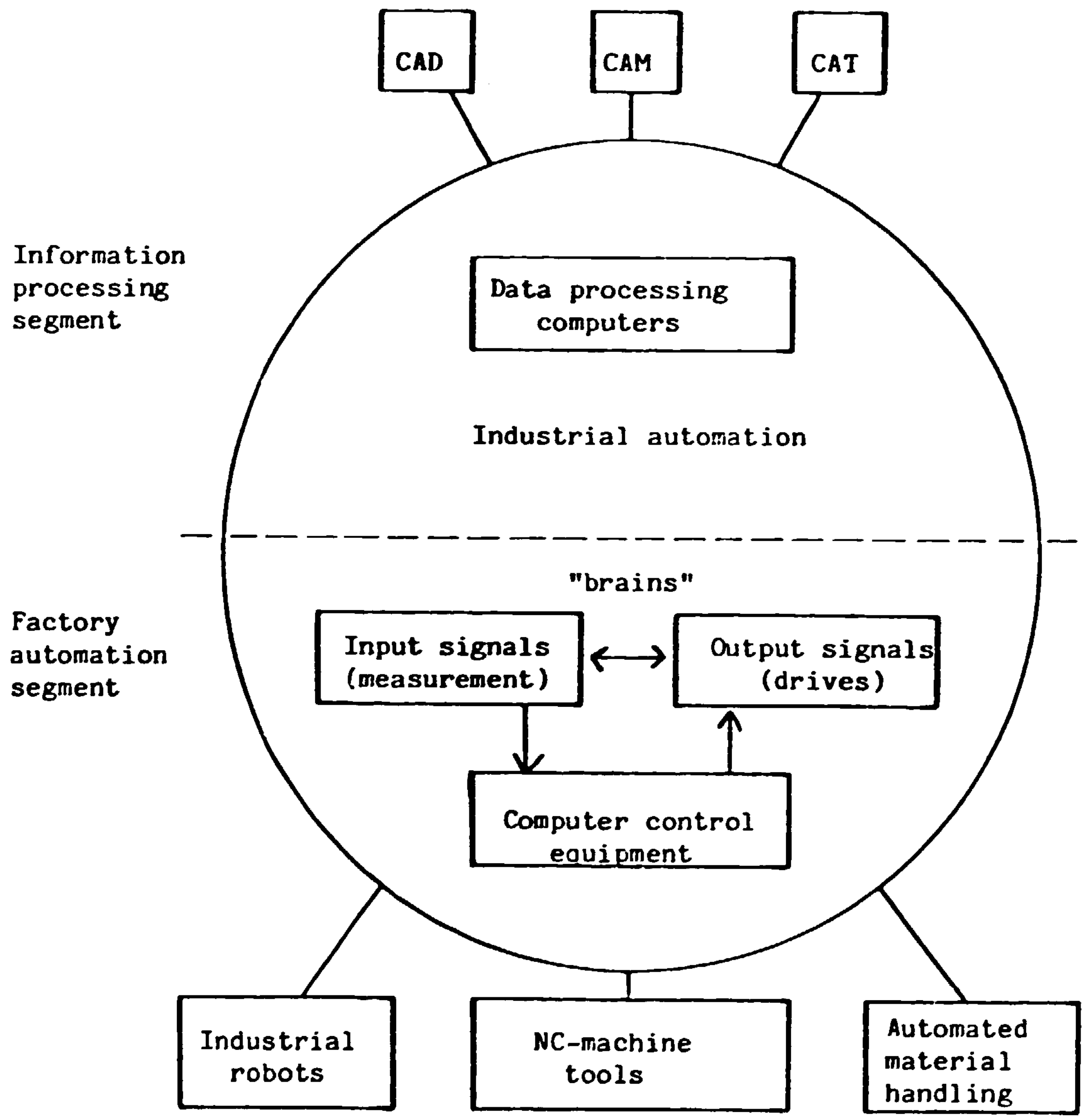
CONCLUDING REMARKS

In this report we have tried to indicate technological trends in the manufacture of integrated circuits and in the manufacture of NC machine tools, where new technologies are conditioned by the preceding development in IC technology. However, it should be borne in mind that advanced NC machine tools exemplify only one, although important, application of IC technology. Equally important is the software development, the development of analytical tools, concepts and programs. These enable the efficient use of NC machine tools in such an integrated way that the manufacturing process is completely changed.

Twenty years ago it would have been possible to set up a small plant with several machines dedicated to making a few products, and manufacture these products year after year making only minor changes. This approach to manufacturing is no longer as simple. Pressing issues such as global competition, demand for large product selection, requirement for greatly improved quality, shortened product life cycles, manufacturing cost, and profit squeeze are the main factors influencing the rapid growth of flexible and computer integrated manufacturing.

The use of computers in manufacturing enterprises was in the past concentrated in the administrative departments. This, among other things, facilitated cost control and sales efforts. The earlier discussion has clearly shown that the development of electronics and its inclusion in the various stages of the manufacturing process itself, has reached such a level that it may in fact be possible to merge the information-processing functions with those of production control-functions. This new situation is simplistically illustrated in Figure X.

Figure X
Interactions between information-processing and production-control functions



Source: C.A. Hodson "Computers in Manufacturing"; Science, vol 215, February 1982.

The rise in the interest in robotics, as well as all segments of factory automation, has focused attention on the overall problem of controlling and integrating the various elements of a fully automatic factory. A robot, for example, is only one element in the arsenal of automation tools to be integrated into any properly designed and coordinated manufacturing automation system.

Automating a process involves supplying controlled motion as well as the ability to monitor the process and activate or deactivate various elements of the process as it progresses. Robots are capable of these functions but they are often also overkill if all that is required is simple movements and turning some switches on and off.

Drawing on the experience within robotics, and a more refined understanding of automation objectives, an ideal automation control system should be modular, expandable, simple, and quick to implement and modify. The modular control system could be kept small and simple, or expanded and replicated for larger, more involved projects. Primary consideration in the system design are to be simplicity, cost, and modularity.

In the editorial of the December 1985 issue of Control Engineering it was argued that the important technological changes are to be found in the control industry. The opening up of distributed control systems will allow inclusion of products of any manufacturer leading to great improvements in the solution of specific control problems.

However, the necessary recognition that control is control, whether control for the process industries or control for discrete parts manufacturing, will prove to be a fundamental change in control industry marketing attitudes that began in 1985, it is argued.

A new era for control system design and marketing was clearly established by the great interest that arose during 1985 in General Motors' manufacturing automation protocol specifications (MAP). More than 100 companies, including both manufacturers and users of control systems, participated in the latest MAP users group meeting.

In the new era based on MAP, distributed control systems will routinely include a wide mix of control products made by many manufacturers, all sharing data with each other via MAP-conforming local area networks. The controls marketplace will be all new and strange for years to come, even to the old-line suppliers, as a direct result of the sudden acceptance of the MAP data utitlity concept.

The stage is now set for computer integrated manufacturing (CIM) which could cover the whole range of activities, from design through to implementation and delivery of the product, finishing only when the final payment is made by the customer. However, the rapid technological changes and the increased wear and tear on plant caused by increased utilisation demands a rapid return on costs. What is then CIM? We will try to explain this by using information from an article which published in the American Machinist. [11]

Computer integrated manufacturing combines human and computerizes functions. The report "Computer Integration of Engineering Design and Production" defines CIM as a manufacturing enterprise in which the following criteria are met:

* All processing functions and related managerial functions are expressed in the form of data.
* This data can be generated, transformed, used, moved, and stored by computer technology.
* This data moves freely between functions throughout the

life of the product. The objective is that the enterprise as a whole have the information it needs to operate at maximum effectiveness.

Information in a CIM system is extracted from fully automated segments of a process for use in controlling, planning, or modifying inputs into the process. Thus, a system that has both an objective and a means of detecting deviations from that objective can take corrective action to decrease the deviation.

It is argued that adoption of CIM technology is essential to the maintenance of recovery of competitiveness by US manufacturers in domestic and world markets. This argument would in all likelihood be equally relevant for companies in other industrialized countries. The companies that are about to invest in product-design or manufacturing-process technology must be aware of the potential benefits of CIM. Competition in manufacturing can only become more intensive and companies that do not move into CIM may face a dim future.

At the heart of CIM technology is the coordination of the data used throughout the manufacturing process - from the perception of the need for a product, through its conception, design and development, production and marketing, to support of the product in use.

A US national committee, referred to in the article, states that a majority of US manufacturers will not be able to remain commpetitive in product quality timeliness of delivery, and cost unless they use CIM. Therefore, cooperative efforts among companies are needed in the US to develop a broader base of US industry to achieve CIM. The Dept of Commerce's R&D Limited Partnership program may offer a useful mechanism for forming consortia.

Finally, trying to summarize the developments in the manufacturing industry by quality, we will quote Professor Astrom, one of the leading experts on process control.[12]

The development of microelectronics will continue, leading to the production of very powerful components for computing, communication, and graphics.

Software will continue to be a bottleneck, although large programs are initiated to improve software production.

Future process control systems will be distributed with man-machine interaction based on high-resolution color graphics. The substantial improvements in computing and storage capability will be used to simplify engienering and man-machine interaction. There may be increased use of symbolic processing and artificial intelligence techniques, like expert systems.

The process knowledge will continue to increase. The process control systems themselves are excellent tools for process studies. This will be enhanced by incorporating computer-aided engineering tools for data analysis modeling and identification. There might be some examples of new processes, which are developed by combining traditional process design with control design.

Much can be accomplished with available sensors. New possibilities for automation may be generated by invention of new sensors.

The increase in computing power will lead to increased use of adaptive control and optimization. Systems that incorporate ideas from artificial intelligence may appear both for diagnosis and intelligent control.

The scope of the systems will expand from instrumentation, through process control, production planning, office automation, and management information. The problem of communication standards will hopefully be solved.

There will be changes in organization and job structures. Efficient use of the new technology will require new organizations. Process control will be less affected than society at large.

ANNEX I

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ANNEX III

PROCEDURES FOR RETRIEVAL OF BIBLIOGRAPHIC MATERIAL

Two international online databases have been primarily identified as most relevant for this study: INSPEC and COMPENDEX.

INSPEC (Information Services for the Physics and Engineering Communities) online database is one of the largest files in the physico-technical domain. The database was started in 1969 and contains presently nearly 2.5 million records published in the areas of computing, control, electrical engineering, electronics, physics and information technology. The current annual growth of the file is of more than 200.000 records.

COMPENDEX (Computerized Engineering Index) covers literature in the fields of engineering and technology as well as biotechnology. This database was started in 1969 and contains presently nearly 1.5 million records. The file increases about 90.000 references a year.

Both databases mentioned above are accessible via ESA-QUEST system. The ESA Information Restrieval Service is a database host organization forming part of the European Space Agency. There are 11 member countries participating in this programme and headquarters are located in Frescati, Italy. The network contains over 105 files including both bibliographic, fact and patent databases.

With the equipment available to us we have been able to get access to ESA either through DATAPAK (directly via the Swedish telecommunications system) or through SUNET lines.

This latter alternative can be used with direct computer connection to the university's computer center, but since the location of the Research Policy Institute lies outside the network area, we had to use a modem for communication.

A tentative online search was set up in November 1985 in order to get acquainted with the ESA network and the QUEST language system. The descriptions used for items identification were the following: "semiconductor", "integrated circuits", "gate arrays", "semicustom", "technological trend" and "economics". Several abbreviations were aslo used: "IC", "ASIC", "VLSI". In order to get an overview of related terms, a text analysis was done with respect to words' frequency.

The resulting references were printed out on line in a format including all bibliographic information as well as abstracts.

In January 1986, a somewhat modified search with more precise descriptions was carried out in both INSPEC and COMPENDEX. Again, ESA-QUEST was used as database host system.

Keywords were identified by Jon Sigurdson, and Yael Taagerud elaborated these with help of the INSPEC thesaurus. This volume is of great help when constructing a search profile since it has very good cross references to related/broader/narrower terms. Since the primary result of the search, based only on keywords, was too large, we limited it to the years 1984-85. This was done on the assumption that the technologies of interest undergo continuous development, and therefore recent articles are most relevant when analysing technological forecasting and economic trends. This was also the reason why we mainly concentrated on journal articles and conference papers rather than books.

The results of these searches were printed out in a format including bibliographic data. The searches were then saved in the network so that we would be able to return to them later on. After a review of the titles, we selected a number of references, and printed them in a format including an abstract. (This was made possible by re-entering the saved searches).

Several articles were selected for full retrieval and we obtained most of them from the University Library in Lund. Since the journal collection covers many of the issues of interest to us, we found more material of relevance while looking for these articles.

Another useful source of information was a standing search profile which we had at the Royal Institute of Technology in Stockholm. The Information and Documentation Center (IDC) of this Institute has established an Information Retrieval service for subscribers who wish to obtain continuous coverage of entries in ESA files. The profile is processed every two weeks, when IDC receives the records from ESA. This service, called EPOS/VIRA is unique in Scandinavia.

The journals which were not available in Lund were located with help of the LIBRIS computer system, which is a Swedish database for literature included in all University libraries and many research/industry libraries. Thus, we could, for example, obtain very important material from the library of the Swedish Defence Research Agency in Linkoping.

The articles herewith obtained together with material acquired earlier on by the authors, constituted the frame for this paper. When looking into issues related to new advanced technologies, there are always plenty of technical descriptions of the latest developments. These aspects could not be overlooked and therefore we even took into consideration short articles/notices in the various electronics journals.

Those journals included also articles of an overview nature which the authors of this report could then compile with the in order to create the ground for a policy-oriented study. Electronics Week (or Electronics as it has changed title several times during the past years), has a good coverage of general issues related to the semiconductor industry. It presents an annual economic perspective in a series of special reports which showed to be very useful.

Another important source was the journal Solid State Technology. Here we found several articles covering many aspects of the technological trends. IEE Proceedings is also of great value in this respect. Articles analysing different economic aspects of the latest developments are also published in Semiconductor International. Many references were also made to VLSI Design which is also an eminent journal on certain issues of this report.

For the definitions of terms we also turned to various handbooks and books. The authors have compiled the present material with the hope to further analyze relevant issues. To this end country cases of the semiconductor industry were partly covered by thus analysing the constraints and consequences especially for developing countries. For this purpose we carried out a search in TEXTLINE database which includes material of less technical character and more economics oriented nature which resulted in interesting references to material about the state-of-the-art in microelectronics in various countries (e.g. Malaysia, Singapore and South Korea).

Very valuable material, mainly about the Indian and Korean cases was obtained also from colleagues who are carrying out research on related issues at the Research Policy Institute in Lund. This material included, among other things, important information of statistical character. Since these researchers are well acquainted with the development of the microelectronics industry in developing countries, we also hope to draw benefits from their comments on this report for future revision.

In the beginning of the 1980s, UNIDO initiated a systematic effort to review and analyse the microelectronics sector and its implications for developing countries. Various reports were produced within different programmes such as the State of the art series on microelectronics. This series presents a description and analysis of the microelectronics sector in various countries.

Also the UNIDO/ECLA Expert Group has produced several reports dealing with the microelectronics industry and its implications for developing countries.

Reviewing some of these reports mentioned above we found that they are interesting each in its own way, but unfortunately, there seems to be no proper integration of the conclusions of all studies done by UNIDO experts up to date. Therefore, we regard all earlier UNIDO efforts as important for our study, since they set the point of departure for fruitful discussion and future development.

A successful effort by UNIDO to disseminate information and stimulate discussion about microelectronics is the MICROELECTRONICS MONITOR. This newsletter has a pleasant way of presenting different issues related to the microelectronics industry. The Microelectronics Monitor is published regularly presenting the trends in technological innovations, but it also has special issues which concentrate on specific related subjects.

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When approaching the subject of NC machine tools, we again had much assistance from various people. Mr Staffan Jacobsson's well documented knowledge of this field was a great resource. We also consulted people working at the Dept. of Production and Materials Engineering at the University of Lund.

The journals studied for this section were partly identified after a database search in COMPENDEX and INSPEC. The keywords used were as follows: "industrial robots", "numerical control", "NC", "CNC", "machine tool", "control system CAD", "controller", "process computer control", "CAM", "manufacturing computer control", "software".

Major journals for this technological field were Industrial Robot, Control Engineering, American Machinist. Groover & Zimmers' book on CAD/CAM has been a valuable reference volume.

IEEE has proved to be a very useful source for information, both regarding technical descriptions and general discussion.

Though not always mentioned as notes, sources of information regarding NC machine tools technology are listed in the bibliography.