THE STRATEGIC EVOLUTION OF THE ROBOTICS INDUSTRY

by

DAVID SCHATZ

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Signature of Author: ______________________
Sloan School of Management, 19 May 1983

Certified by: ______________________
Zenon S. Zannetos, Thesis Supervisor

Accepted by: ______________________
Jeffrey Barks, Director of Master's Program

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ABSTRACT

The robotics industry has received tremendous attention in the popular press, as well as in the academic and financial communities. Robot technology is looked upon as a key to restoring the U.S.'s industrial preeminence. This thesis examines the evolution of this important industry, paying particular attention to the factors that have caused it to evolve as it has, and to what we might expect the industry's future to be. The first two sections discuss robot technology and applications. The balance of the thesis is devoted to documenting and analyzing the history of the industry, with an emphasis on strategic and structural issues.

Robots are systems comprised of many distinct component technologies. Some of these are more dynamic than others, thus having an effect on a firm's ability to stake out a position based on existing technological expertise. Computer technology, especially control and sensor processing software, is expected to have the greatest impact on the industry. The technological diversity has created opportunities for a broad range of firms, and has been an incentive to form interfirm relationships. The high applications engineering content of robot systems has forced robot suppliers to provide a high degree of customer support, and has made niching by application an effective strategy. The early international diffusion of robot technology has had important effects on the U.S. robot industry. Japanese and European firms now present a substantial competitive threat to U.S. firms, as well as providing a source of partners for U.S. firms seeking to enter the industry by licensing proven robot technology.

Furthermore, the early Japanese adoption of robots contributed to their achieving a position of worldwide manufacturing superiority. This has in turn stimulated the demand for robots in the U.S. and Europe, as firms are trying to regain their competitiveness.

Because of the competitive pressures in the robot industry, and the ability of firms to carve out niches, it is expected that the industry will become less concentrated. As end users become more sophisticated, it is likely that they will demand that robots be available on a modular, component basis. Thus, robot components will "commodities"- with the resulting implications for competitive strategies and industry profitability.

Thesis Supervisor: Prof. Zenon Zannetos

Title: Professor of Management

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1. Introduction

The evolution of industry is one of the purest of Darwinian processes. Through a combination of luck, strategy and execution, firms within an industry prosper, fail or mutate in order to survive. Since firms in part base their strategies on expectations of industry growth and evolution, it would be useful to understand the implications of the various stages of industry evolution on a firm's strategic choices. This thesis examines a particularly dynamic and newsworthy industry - robotics - in an attempt to understand the strategic behavior of firms as a function of industry evolution.

The robotics industry has received a tremendous amount of attention in academia, the financial world and in the popular press. Industrial automation is looked upon as one of the keys to restoring this country's industrial pre-eminence. The potential economic and social impacts alone justify the study of this industry. In addition, there are a number of underlying characteristics and empirical phenomena that make the robotics industry interesting from a strategic standpoint. It is driven by a diverse array of technologies - mechanical design, artificial intelligence, materials science, to name just a few. Robotics is also a subset of a broader technology popularly called "factory of the future" - the large scale automation and networking of factory equipment. This diversity of technology creates opportunities for many firms. Indeed, the industry has attracted a large number of entrants from many different technology tracks. These firms range from thinly funded startups to some of the largest companies in the world, including IBM and General Motors. But which of these firms will succeed, and what are the appropriate strategic responses to the technological diversity? One of the more interesting responses has been the plethora of joint ventures and licensing agreements in the last few years. Another unique response has been the unprecedented industry commitment to funding academic research in robotics. Understanding the role of technology and technological diversity can help not only company strategists, but also public policy makers concerned with technology based industry.

Another interesting and important phenomenon is the strong international flavor in the industry. Although robots were "invented" in the United States, Japan has taken the lead in implementing robot technology. In the last five years, American companies looking to enter the burgeoning robot market have gone to Japan and Western Europe to license proven robot technology. This importing of robot technology is yet another violation of the conventional "international product life cycle" model in which technology is first developed in the United States, then exported to the rest of the world. And what is especially ironic about the robot industry is that given our high labor costs, a productivity improving innovation such as robots should have caught on here before in countries with lower relative labor costs. What was it that caused Japan to adopt robotic technology so quickly? And given the head start that Japan and some European countries have in robotizing their factories, how can United States companies compete in this truly international market? These questions are also important to both corporate strategists and public policy makers.

The purpose of this thesis can be thought of as answering the following three questions about the robot industry:

1. Why did robot technology give rise to a distinct industry?

2. What factors have caused it to evolve the way it has?

3. What might we expect to happen in the industry in the future?

I will address these general questions by documenting and analyzing the historical evolution of the industry, from its inception in the late 1950's to the present. Particular attention will be paid to understanding individual firms' motivations and strategies for entry into the industry as well as their competitive marketing and technological strategies, and how these factors have changed over time. The interesting empirical aspects of the industry mentioned previously will fall out as the results of underlying economic and technological forces.

In order to lay a framework for understanding individual firms' strategies, the first two sections will discuss robot technology and applications. The next section will then discuss the evolution of the robot industry, both descriptively and analytically. In the concluding section, I will answer the three basic questions spelled out above, and attempt to generalize from the experience of the robot industry.

2. Robotic Technology

This Section will outline the diverse technologies that are embodied in what is popularly called "robotics". A premise of this thesis is that the industry is interesting to study because of this diversity of technologies. The diversity creates opportunities for firms in a wide variety of industries, ranging from those who develop component technologies to those who function as system integrators.

It will become clear in this Section that the technologies with the greatest potential impact on the industry are those based on computer hardware and software. The mechanical technology embodied in the robot is quite mature, and unlikely to change dramatically or to stimulate growth or change in the industry. Such generalizations about technological change and its impact on the industry will help us understand and evaluate the strategic choices of robot manufacturers.

2.1 Classification and Definition

Robots are systems of widely varying complexity, intelligence and cost. The different types of robots generally do not compete for given applications and certainly all robot manufacturers do not compete with each other. Robots are generally categorized by control strategy, for it is the degree of control and intelligence that determines the suitability of a robot for a particular application. A simple schema for categorizing robots by control and relative technological maturity is:

(1) non servo, point to point robots - the simplest robots usually used to simply pick up and move an object. Most technologically mature. (30-35% of United States robot base) [20],

(2) servo controlled, continuous path robots - more complex robots that can be used for assembly, painting and welding as well as materials transfer (65-70% of United States robot base), [20] and

(3) sensor based, highly intelligent robots - the most complex

robots - they can interact with their environment and are generally used for assembly and complicated processing. State of the art technology. (less than 5% of existing United States robot base) [20].

This chema will be more fully explained in the discussion of control technology, and will later be used in analyzing the structure of the robotics industry.

There has been some controversy due to the various definitions of robots, especially with respect to the broad Japanese definition. A comparison of the "official" definitions of the Japanese Industrial Robot Association (JIRA) and the Robot Institute of America (R.I.A.) appears in Figure 1. For the purposes of this study, the more restrictive R.I.A. definition is appropriate. Included in the Japanese definition are devices better described as "hard-automation" or "tele-operators", rather than as industrial robots.

2.2 Component Technologies

The next few sections will outline robotic technology by looking at the important components in a robot system. These components are:

1. manipulator or arm

Definitions and Classifications of Industrial Robots

Japanese Industrial Standard JIS B0134-1979

Manipulator A device for handling objects as desired without touching with the hands, and it has more than two of the motional capabilities such as revolution, out-in, up-down, right-left travelling, swinging or bending, so that it can spatially transport an object by holding, adhering to, and so on.

Robot A robot is defined as a mechanical system which has flexible motion functions analogous to the motion functions of living organisms or combines such motion functions with intelligent functions, and which acts in response to the human will. In this context, intelligent functions mean the ability to perform at least one of the following: judgment, recognition, adaptation or learning.

Classification by input information and teaching method

Manual manipulator A manipulator that is directly operated by a man.

Sequence robot A manipulator, the working step of which operates sequentially in compliance with preset procedures, conditions and positions.

Fixed sequence A sequence robot as defined above, for which the preset information cannot be easily changed.

Variable sequence A sequence robot as defined above, for which the preset information can be easily changed.

Playback robot A manipulator that can repeat any operation after being instructed by a man.

Numerically controlled robot A manipulator that can execute the commanded operation in compliance with the numerically loaded working information on e.g. position, sequence and conditions.

Intelligent robot A robot that can determine its own actions through its sensing and recognitive abilities.

Source: Yamamoto, 1981, P. 5

U.S. View

INDUSTRIAL ROBOTS all have armlike projections and grippers that perform factory work customarily done by humans. The term is usually reserved for machines with some form of built-in control system and capable of stand-alone operation. But in Japan, it also includes manipulators operated by humans, either directly or remotely.

Classification by Servo Type

NON-SERVO ROBOTS

A PICK-AND-PLACE ROBOT is the simplest version accounting for about one-third of all U.S. installations. The name comes from its usual application in materials handling, picking something from one spot and placing it at another. Freedom of movement is usually limited to two or three directions — in and out, left and right, and up and down. The control system is electromechanical. Prices range from $5,000 to $30,000.

A SERVO ROBOT is the most common industrial robot because it can include all robots described below. The name stems from one or more servomechanisms that enable the arm and gripper to alter direction in midair, without having to trip a mechanical switch. Five to seven directional movements are common, depending on the number of "joints," or articulations, in the robot's arm.

A PROGRAMMABLE ROBOT is a servo robot directed by a programmable controller that memorizes a sequence of arm-and-gripper movements; this routine can then be repeated perpetually. The robot is reprogrammed by leading its gripper through the new task. The price range is $25,000 to $90,000.

A COMPUTERIZED ROBOT is a servo model run by a computer. The computer controller does not have to be taught by leading the arm-gripper through a routine; new instructions can be transmitted electronically. The programming for such "smart" robots may include the ability to optimize, or improve, its work-routine instructions. Prices start at about $35,000.

A SENSORY ROBOT is a computerized robot with one or more artificial senses, usually sight or touch. Prices for early models start at about $75,000.

AN ASSEMBLY ROBOT is a computerized robot, probably a sensory model, designed specifically for assembly-line jobs. For light, batch-manufacturing applications, the arm's design may be fairly anthropomorphic.

Source: Business Week, June 9, 1980, P. 64

FIGURE 1

Source: Gevarter, 1982

2. activator or power source

3. end effector or tool

4. sensors

5. controller - hardware and software.

In addition, other important technologies including parts fixturing, local area networking and the concept of "Factory of the Future" will be discussed.

2.3 Manipulators

The manipulator is the mechanical "arm" of the robot and, as previously mentioned, the most mature and well developed of all the components. The arm is basically a system of linkages and joints that can accomplish motion with varying degrees of freedom, or axes of movement. Manipulators are generally categorized by basic architecture and further classified by the number of degrees of freedom. Typically, three degrees of freedom are provided by the arm itself and from 1-3 are provided by the "wrist." The four basic manipulator architectures are: (see Figure 2)

1. anthropomorphic - articulated or jointed arms resembling human arms

EXISTING ROBOTIC MANIPULATOR TYPES

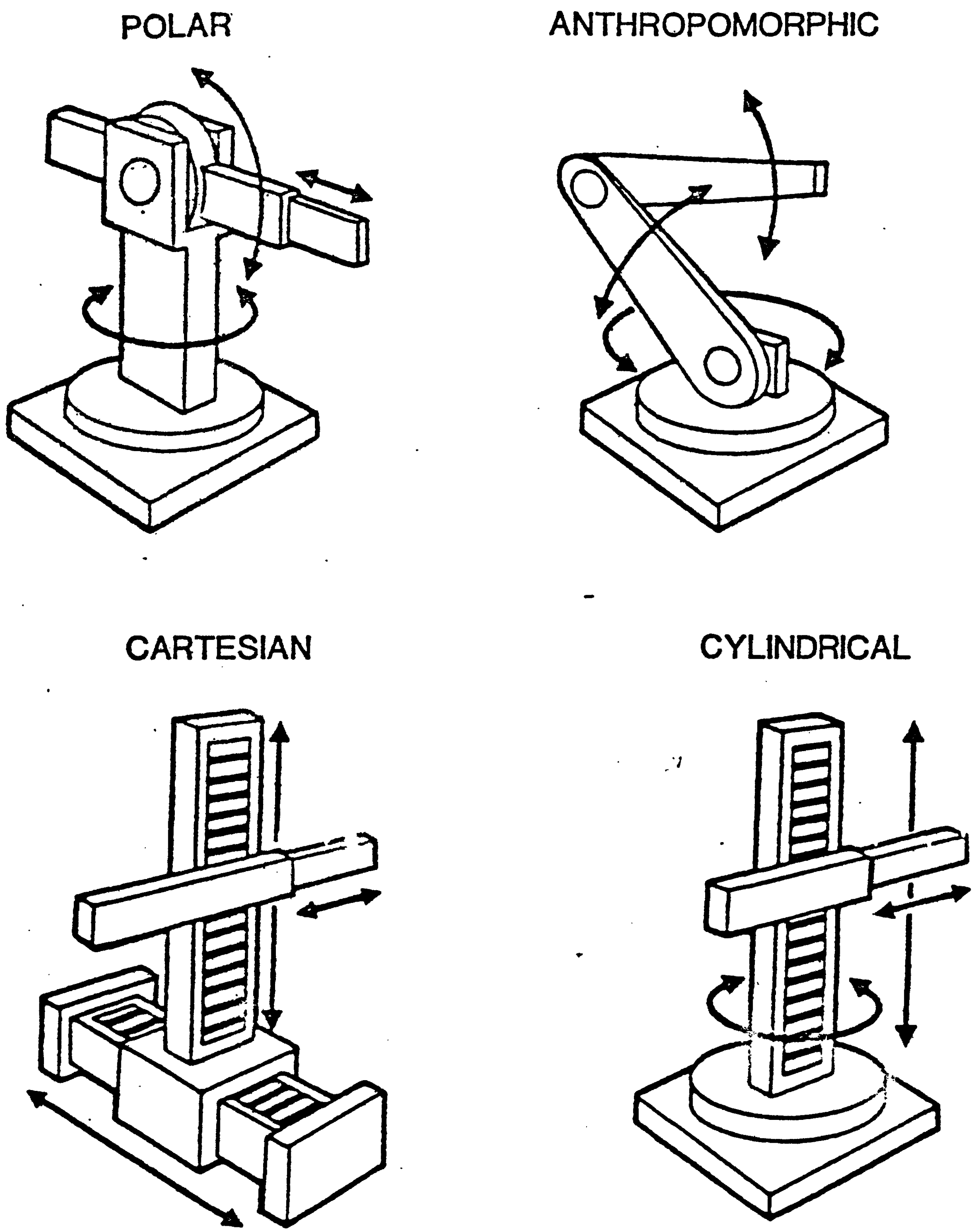


FIGURE 2

Source: Yankee Group, 1981

2. cylindrical - arms mounted and travelling around a central axis

3. polar - arms mounted on a central axis but also having a tilting capability

4. cartesian - arms that move along three perpendicular tracks.

Anthropomorphic arms have the advantage of the greatest working volume for a given robot size. They are generally the most complex and fragile of the four architectures and are used in applications involving light payloads, such as light assembly or spray painting and arc welding.

Cylindrical arms have been used primarily in machine tool loadlng and unloading applications, but their inability to tilt severely constrains their usefulness. It is one of the earliest (and simplest) of arm designs and is gradually being displaced by the more versatile but similar polar arms.

The polar arm is quite similar to the cylindrical arm, except that it has the extra degree of freedom that allows it to tilt. The polar arm can be though of as the "original" arm design but it is far from obsolescent. Its usefulness in spot welding applications in the automobile industry in part drove the robot "explosion" of the 1970's. In addition, it is used in many materials transer operations.

The cartesian arm is the least anthropomorphic of all the robot architectures. Its motion is determined by combinations of linear movement in three dimensions, so computationally it is the simplest to control. As a result, cartesian robots are very accurate and are finding use in high precision electronic assembly applications. In addition, most of the simple pick and place manipulators are cartesian devices.

Although arm technology is well developed and relatively mature, incremental improvements in speed, precision and accuracy will be achieved. However, most of these improvements will be realized through software or controller improvements rather than through changes in mechanical design nature. Perhaps the most important changes in arm design will be in the use of lighter materials such as graphite composites which will allow for much lighter and, therefore, faster and easier to control robots.

An interesting and slightly controversial design issue is the relative importance of anthropomorphic features in robot arm design. In his forecast of robot technology, Albus of the National Bureau of Standards predicts that the " ... utilization of biomechanical concepts will result in superior robot structures"[20]. But do we want to use the human arm as a model for robot arms? Professor Warren Seering, M.I.T., states " ... Any attempt to emulate human behavior with a robot is a mis-direction ... It is predicated on the idea that humans, particularly human arms, are optimally designed to do factory work. And this is not true ... The primary advantage that robots will have ... will be based not on their ability to mimic humans but on their abilities to perform tasks in ways which humans cannot."[47]. This is an important issue that has bearing on the direction of robotic research in general. It has implications for robot manufacturers as well. Should product development be directed towards highly intelligent, general purpose robots that can emulate human behavior and motions, or towards simpler systems that utilize manipulators designed to perform specific tasks? This important distinction between highly intelligent, general purpose robots and simpler but more specialized robots raises strategic questions as well as technical ones. These questions will be discussed in Section 4.

2.4 End Effectors

The end effector is the robot's "hand" - the device that contacts the work piece or the tool that processes it. These devices can range from "grippers" which open and close, to spray painting guns or welding torches. The latter are simply conventional tools that have been adapted for robotic arms rather than human arms. The grippers and other tools that are used to handle or process an object are usually unique to a particular application and are often designed by the end user. They use mechanical magnetic and suction techniques to manipulate the work piece. A great deal of effort is directed towards developing general purpose grippers. These grippers will have integral force, tactile, proximity and even vision sensors that will allow the gripper to be adaptable for use with a variety of part configurations. It appears that the trend in gripper development is also along anthropomorphic lines. The strategic and technological choice is, again, whether to develop flexible, general purpose end effectors or specialized, custom ones. Clearly, the more interesting (and potentially profitable) development problem is the universal, general purpose gripper. However, the more practical and expedient approach is the use of specialized end effectors.

2.5 Actuators

The actuating system provides the robot arm with motive power. These systems are generally pneumatic, electric or hydraulic. The choice of which system to use in a given robot application depends on requirements for strength, speed and cost. Certain applications use combinations of drive technologies. These technologies are rather mature, having been developed for use in aerospace and industrial control applications.

Pneumatic systems are the simplest, fastest and most inexpensive of the drive systems. However, they cannot provide much strength and are not well suited to continuous path control. Thus, pneumatic drives are usually used in simple pick and place applications with light payloads.

Hydraulic drives are much more powerful than pneumatics and can be more closely controlled. These drives make use of compressed hydraulic fluids and thus require auxiliary pumps and storage tanks. They have been criticized for leaking and causing a great deal of machine downtime. However, they are quite versatile, well understood and relatively inexpensive. It is the most widely used robot drive system, especially for larger robots.

There are a range of different types of electric drives ranging from simple, inexpensive stepper motors to high power DC servo drives. ("servo" simply implies that the motor is part of a closed loop feedback control system; most electric and hydraulic drives are "servo controlled") Electric drives are usually used in applications having very large payloads. In addition, the development of relatively low cost AC servo motors is leading to the gradual displacement of hydraulic systems in smaller robots, especially those used in high precision assembly applications. Electric motors have the distinct advantage over hydraulic drives of not using a potentially leaky and troublesome working fluid, and of being more energy efficient. However, electric drives are generally more expensive than hydraulic drives.

Robot manufacturers generally do not manufacture their own actuator systems, rather, they are built up using standard electric, hydraulic or pneumatic components purchased from a drive or controls supplier and adapted for use in robot systems. Research and development work is aimed at improving the reliability and strength/weight ratios of drive systems, with most of the effort focused on electric drives.

2.6 Sensors

Sensors allow the robot to interact with its environment - to touch, feel and see the work piece. Very few robots today make use of sophisticated sensors. The most commonly used sensors are electro-optical parts presence sensors which tell the robot if the work piece has been grasped or if it is properly oriented. Electro-optics is a basic industrial control technology that has been applied to robotics. However, the development of "tactile" or touch sensors, vision systems and force feedback are very much driven by robotics applications, and may be considered to be seminal robotic technologies. It is important to note that the application of sophisticated sensing devices is not strictly a hardware problem, but is also a difficult software and control problem.

Force feedback is accomplished using existing strain measuring devices adapted for robotic systems, as well as making use of internal measurements of hydraulic pressure or back electro motive force (emf) in the robots drive system. The problem is not so much in measuring forces, but in knowing what to do with the measurements and how to process them in real time. Few production robots make use of force measurements. Tactile, or touch sensing is now accomplished using simple micro switches. Development is aimed at an "artificial skin" with an imbedded array of touch sensors. In addition to being a complex mechanical and material science problem, software must be developed that will process "tactile" input quickly and yield meaningful information that the robot controller can take action on. The purpose of sophisticated tactile sensors is to give the robot the capability to determine the position, orientation and identity of work pieces by touch alone. The Delphi forecast of robot technology being undertaken by Smith and Wilson predicts that as many as twenty (20%) percent of all robots sold in 1990 will be equipped with some type of tactile sensing capability[4].

Vision is perhaps the most intriguing and complex of the robot sensing technologies. In fact, an entire industry is springing up in response to the need for robot vision, as well as for vision for other industrial applications (e.g., inspection, mensuration). The potential capabilities of vision in robotics are:

1. recognition of work pieces

2. determination of work piece position, orientation
3. extraction and location of salient features of work piece
4. in process inspection and verification.

The first three applications will allow the robot system to circumvent the need for extensive parts fixturing and pre-orientation and, thus, move robotics closer to the concept of truly general purpose, flexible automation. An example of this type of application is the bin picking problem, in which the robot must be able to pick a specific work piece out of a jumbled bin and manipulate it into the proper orientation. Many argue, however, that bin picking is an example of what a robot should not do. They maintain that the parts should be presented to the robot in a prescribed and predictable manner, via a controlled parts feeding and fixturing system. Ultimately, this is not a philosophical question of what robots should/should not do, but an economic question in which the cost of such an intelligent vision capability must be compared to the cost of presentation/fixturing as well as considering relative performance of the two approaches. Smith and Wilson's Delphi forecast suggests that as many as twenty-five (25%) percent of all robots sold in 1990 will be equipped with some type of vision capability.[4]

Simpler applications of vision in use today include in-process measurement and gauging of the work piece. Vision is also used to track the weld seam for an arc welding robot. In addition to complex vision systems, proximity and ranging devices that make use of infrared or ultrasonic techniques can give the robot a rudimentary vision capability.

Vision is very much a software technology - the development of algorithms that interpret the digital picture input to the computer. What makes the vision problem so difficult is the ambiguity and subtle detail present in most applications, and the tremendous amount of data that must be processed to describe an image. The systems on the market today address limited problems such as seam tracking or gauging rather than the "general" vision problem. Some commercial systems are beginning to address the bin picking problem, but a reliable, general purpose bin picking capability is a few years away from commercialization. Hardware will continue to improve, though it is likely that hardware will become a "commodity" component of vision systems, with software accounting for the proprietary value added. The most promising hardware development is the application of VLSI technology to dedicated vision processing computers. These dedicated computers will be able to process a tremendous amount of data much faster than the general purpose mini/micro computers that are now used. In addition, the television cameras that are used in vision systems will be miniaturized and have improved resolution with the continued development of charge couple device (CCD) technology (versus existing raster technology). It is felt the improved sensing capabilities will drive the development of versatile, general purpose robots. It is likely that sensors will be offered as discrete modules that can be fit to appropriate applications. The technology is sufficiently useful and promising enough today to justify the creation of a robotic sensor industry. In addition, there is tremendous room for incremental improvements in the technologies and, thus, for continued growth in the sensor industry.

2.7 Controllers

Robot controllers range in complexity from simple sequencers to sophisticated mini computers. In all cases, though, the controller performs three basic functions:

1. provides for man/machine interface
2. stores programmed functions in memory

3. executes functions through control of manipulator/actuator.

Complex controllers simply accept sensory feedback to increase the level of control over the robot.

When discussing and categorizing robots, it is more useful to consider the overall robot control strategy, rather than the specific hardware that is chosen for the controller. The choice of hardware is certainly important, but is is entirely determined by the control strategy chosen for the robot. This control strategy is implemented by combining a controller, software, and the appropriate sensors and activators into a control system.

The simplest control strategy for a robot is non servo, or open loop control. The robot is controlled using a sequencer and mechanical stops or stepper motors which determine the end points of the robot's motion, but have no control of the motion itself. Such control is appropriate in applications termed "pick and place", where path and velocity control are not important. Examples of such applications include machine loading/unloading and materials transfer. The advantages of non servo control are: relatively low cost, simplicity in programming and operation, reliability and high speed. The disadvantages of non servo control lies in its inherently limited positioning capability. These robots are taught by programming the desired sequence of motions and physically adjusting the end stops for each axis of movement. Even though the sequence is programmed in software, the fact that end points must be physically positioned limits non servo robots to the performance of one program at a time.

The more sophisticated and flexible class of robots are servo controlled. This means that the manipulator is instrumented such that the controller can determine the arm's velocity and orientation in space and, thus, can effect closed loop control of motion. This closed loop allows close control over the robot's path (i.e., velocity, acceleration) and eliminates the need for physically positioned end stops. Point-to-point servo robots function similarly to point-to-point non-servos, except that end points are programmed rather than physically positioned. They are also used primarily in machine tool loading, parts handling and spot welding tasks. In addition, because of their positioning accuracy and programmability, servo controlled point-to-point robots are well suited to more complex assembly and parts insertion tasks. Continuous path servo controlled robots give the user software control of not only end points but of path velocity and acceleration. These robots are used in applications such as spray painting and arc welding in which path control is critical. Servo controlled robots are usually taught by physically "walking" the arm through its task or by leading it through its task with a joystick remote controller while recording the motion in memory. Many robots can also be programmed "off line" using a robot programming language and even making use of computer aided design (CAD) data bases. Thus, the advantage of servo control is in the close control over positioning and path that is afforded and in their programmability. Because these robots are more complex and highly instrumented, they are generally more expensive, less reliable and more difficult to maintain than non-servo robots.

The most sophisticated class of robots are sensor based and highly intelligent - such that they can adapt their pre-programmed instructions to changes in the environment. These are basically servo controlled robots to which vision, tactile and/or force sensing equipment is added and for which a more powerful control computer is used. These state-of-the-art or so-called "second generation" robots are largely confined to research labs - and to the imaginations of robot designers. However, robots with rudimentary sensing capabilities are being used in assembly and arc welding applications. The key to commercializing this class of robots lies in sensor development and in control software.

Robot controllers make use of existing control hardware adapted for robot applications. For example, the solid state sequencers and programmable controllers used for most point-to-point robots are standard industrial controllers. The more sophisticated servo controlled robots use standard mini and micro computers, such as the DEC LSI-II, Motorolla MC68000, or IBM Series I, adapted and specially programmed for robot control applications. The trend in controller design is towards modularity. A truly modular controller would be able to be interfaced with any type of robot arm and actuating system, and would be able to support whatever sensing "modules" were required. However, modularity to the point where different manufacturers modules can be integrated will come only with industry enforced product interfacing standards. This important issue will be discussed further in Section 2.8.

As has been mentioned many times in this discussion, software development is having and will continue to have a major impact on the robotics industry. It is software, or as it is popularly called, "artificial intelligence," that will enable the use of general purpose, sensor based robots in applications too difficult for today's robots. Software development can be thought to be addressing two classes of problems. The first relates to basic robot control needs such as optimization of trajectory, increased speed, fault tolerance, error recovery, sensor processing and multiple arm synchronization. The second class relates to the need for high level executive programming languages that allow the end user to program the robot for a given application. These higher level languages make use of sub-programs that address the basic robot control tasks, but present the user with a simple, "friendly" interface. These programs allow the user to program in a manner more directed to the work piece rather than the manipulator. For example, commands such as "insert component A in component B such that holes line up" are used rather than programming specific manipulator trajectories and sequences. Modularity and interchangeability of software are very desirable from the users standpoint, so that programs can be developed for a particular robot system but used on any other system performilng a similar task. However, the different robot manufacturers are developing their own programming languages and control software with little regard for interchangeability.

2.8 Factory of the Future

The previous Sections have concentrated on the robot's component technologies. However, the robot system can also be considered to be a component of the automated "factory of the future" - albeit a very important component. Figure 3 graphically illustrates the general concept of Factory of the Future - the computerized working of CAD, automated warehousing, automated assembly manufacturing, production control and puchasing systems via a computer communications network. Robots are expected to be incorporated into flexible work stations, also referred to as "machining cells" or "adaptable programmable assembly systems." These work stations will make use of robots in conjunction with other automated processing and materials handing equipment. By linking these work stations with other factory computer systems, it is hoped that the engineering and production control documentation and scheduling process can be streamlined resulting in a much more efficient manufacturing plant. It has been estimated that as much as 60% to 70% of manufacturing costs relate to these administrative manufacturing functions [38].

In addition to the component systems of the F.O.F. concept, the development of local area networking (L.A.N.) systems will be a driving force in factory automation. Already, companies such

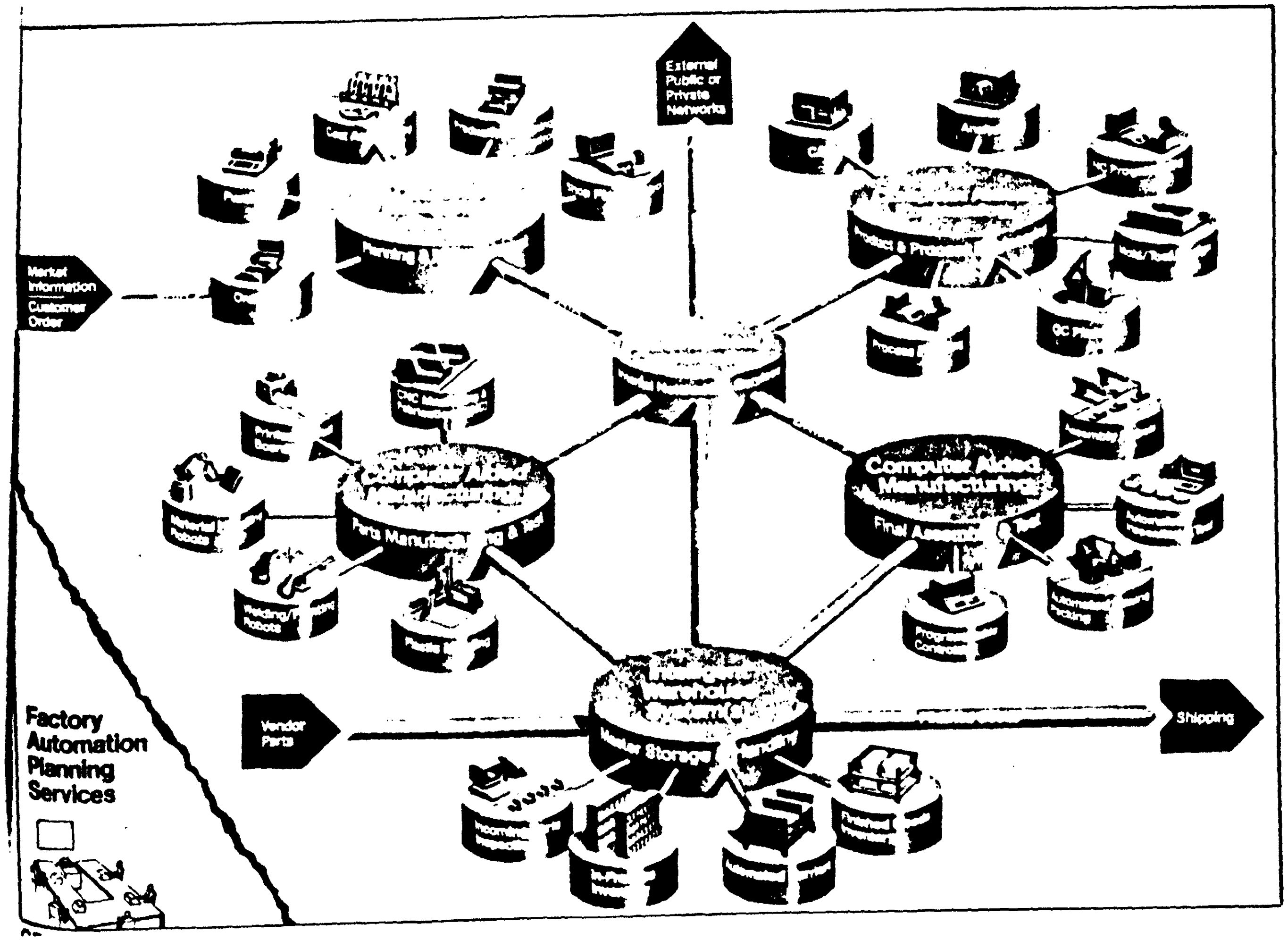


FIGURE 3

FACTORY OF THE FUTURE

Source: Mini-Micro Systems, 1982

as General Electric, DEC, Texas Instruments and Hewlett-Packard market L.A.N.'s designed for the industrial market. These systems are similar to those offered for office automation, but they must function in a much more hostile and failure sensitive environment. And as in the office L.A.N. market, the manufacturers are split into baseband versus broadband camps. Modularity and the ability to easily interface with many types of systems will be a critical requirement for factory L.A.N.'s. However, it remains to be seen if L.A.N. manufacturers can do this for factory systems, since they have struggled with the problem in EDP environments for the last twenty years.

The most likely starting point for this integration of manufacturing systems is the interfacing of CAD systems with robot controllers. This interfacing will allow for off-line program development and will take advantage of the data bases generated for CAD purposes. CAD and robot suppliers are already beginning to offer systems with simple interfacing capabilities. Smith and Wilson forecast the following trend in CAD/robot interfacing:

PERCENTAGE OF ROBOTS SOLD, DIRECTLY INTERFACED WITH A CAD/CAM SYSTEM [4]

	1985	1990	1995
ALL INDUSTRY	5%	15%	30%

2.9 Standards

It is clear that since robots are built up by interfacing a number of component systems, standardization of component interfaces or the lack thereof, will be a major factor in the industry. However, standards are usually promulgated if there is a dominant industry force, either powerful manufacturers, customers, or government agencies (often customers). At this time, work on standards is just beginning.

The Robot Institute of America is the leading robotics trade association and is taking the lead in developing standards. The RIA has identified eight primary areas that need standards and is beginning to assemble joint industry/user/academic committees to address these areas [52]. The eight areas are:

1. safety

2. tooling interfaces

3. sensory interfaces

4. mechanical systems

5. performance specifications

6. construction

7. communications

8. programming languages

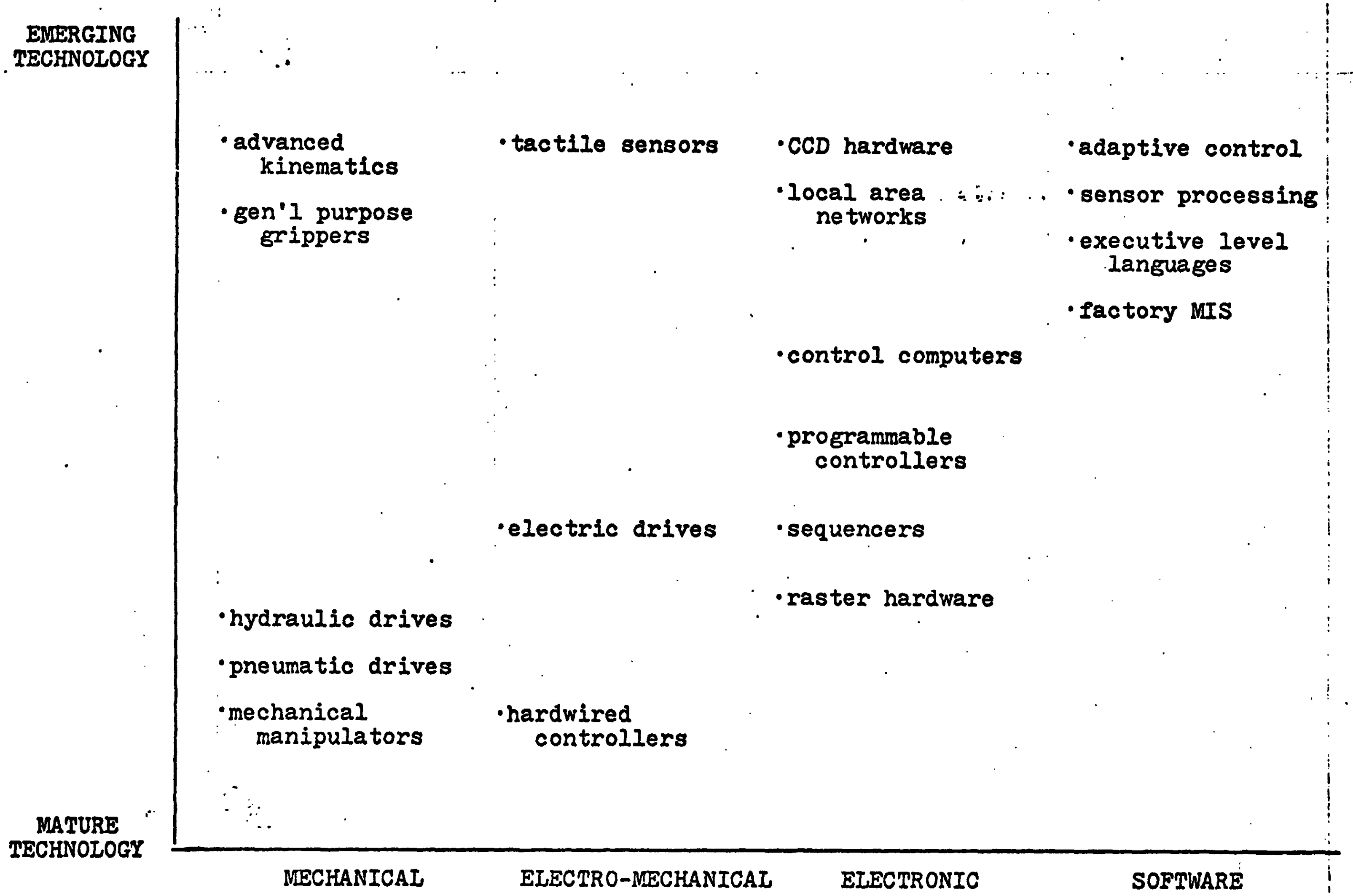
Safety and tooling interfaces, two of the least controversial areas, have already received considerable attention and standards in these areas are forthcoming. However, the other areas are less technologically "settled" - and manufacturers are reluctant to restrict their options by agreeing on technical standards. Meaningful standards in these more dynamic areas are unlikely in the next decade. Smith and Wilson forecast that neither software standards nor a common programming language will be adopted until 1990[4]. Standards for the other hardware areas are not expected until 1985.

The strategic impact of robot standards will be discussed in Section 4.

2.10 Robot Technology - Summary

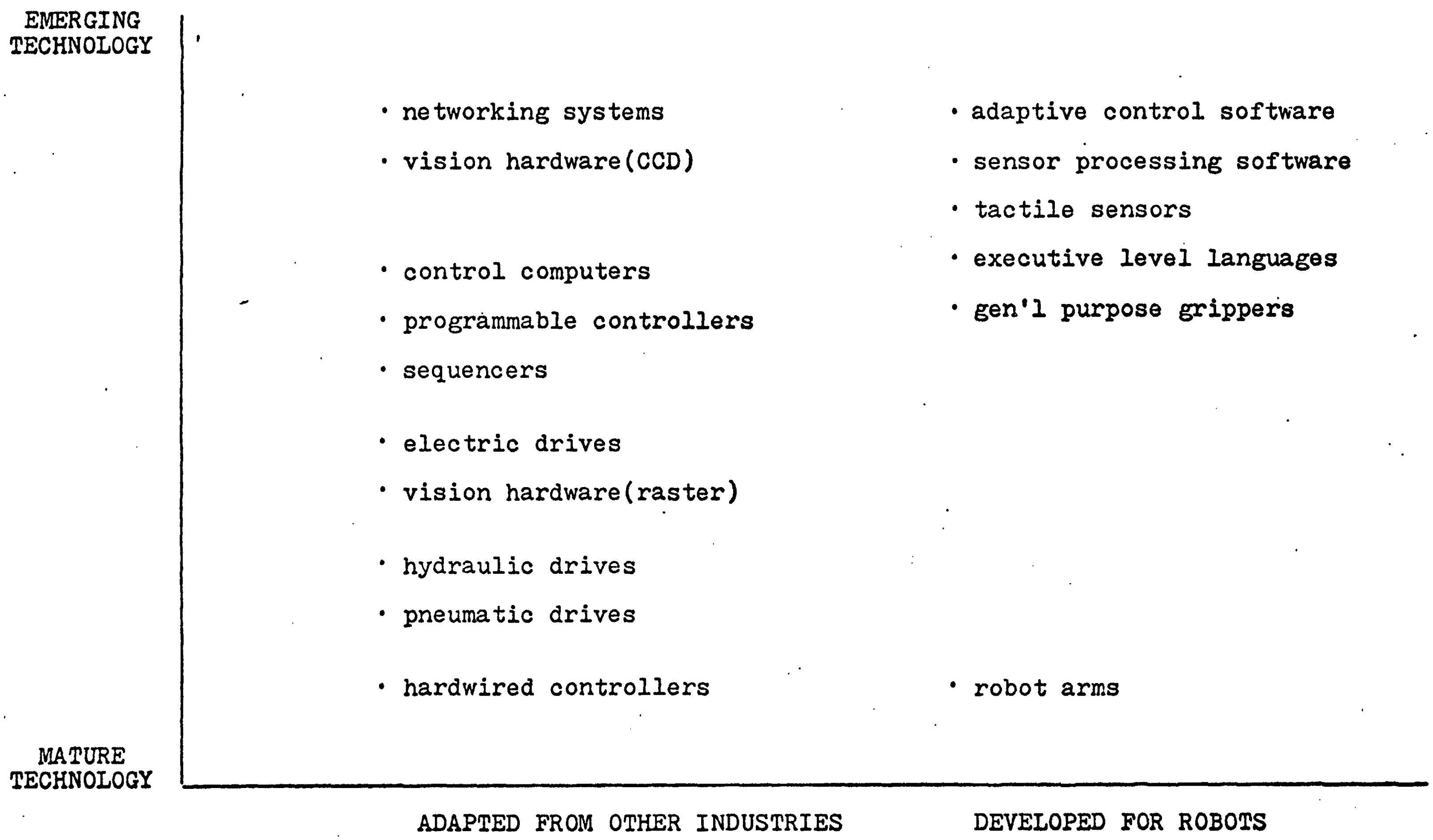
This Section showed the diverse range of technologies that are integrated into robotic systems. Some of the technologies, manipulators and actuators for example, are quite mature and incremental improvements in them are unlikely to stimulate significant change in the industry. Control and sensory processing software technologies are rapidly advancing and will quite likely be the driving force in the development of highly intelligent, adaptable robot systems. Most of the hardware systems used in robots, including comtrols, computers, drives and television cameras have been developed for use in other industries but are adapted for use in robots. Grippers and tactile sensors, however, are examples of hardware technologies driven by the robot industry. Figures 4 and 5 characterize the components of a robot system along a number of dimensions including technological content and maturity and the extent to which a component represents a "seminal" robot technology versus being an existing, adapted technology. These characterizations are very important in understanding the strategic choices faced by the industry. For example, which technologies can be easily reversed, engineered and copied? Which are likely to help the firm stake out a proprietary, defendable position? Which technologies represent the best track for firms looking to diversify into robots? These issues will be examined closely in the discussion of strategy in the robot industry.

It is clear that the technological frontier in robotics is the development of sensor based, highly intelligent general purpose robots. Such systems represent the most interesting research problems, and are intriguing to engineers, managers and even the public at large. However, there seems to be an "anthropomorphic bias" in robot development[48]. Technologies such as tactile and vision sensing, general purpose grippers and artificial intelligence are being applied to give the robot human-like sensory perception, dexterity and decision making capability. Much of the research and development is implicitly



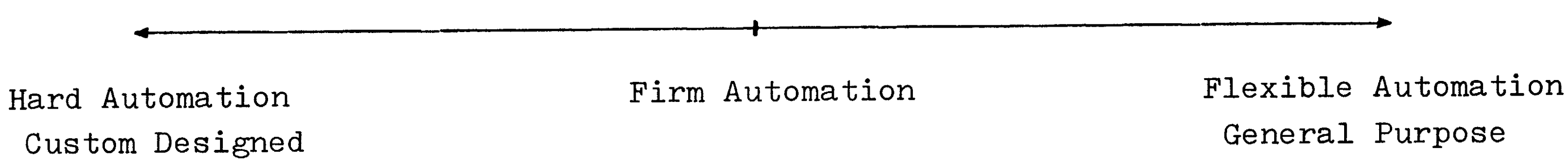
TECHNOLOGICAL MATURITY VS. CONTENT

FIGURE 4



TECHNOLOGICAL MATURITY VS. ORIGIN
FIGURE 5

and explicitly aimed at replacing general purpose human labor in factories. Sociological and moral implications aside, should robot development be aimed at replicating human functions and capabilities, or towards designing automation systems optimized for doing particular tasks? The question really is one of economic tradeoffs between highly intelligent, general purpose robots adapted to a particular application (much as a human worker is) and more specialized robot systems with less flexibility and intelligence, but tailored for a specific application. The strategic question facing the robot manufacturer is where in the continuum shown in Figure 6 the company should be positioned. Seering [48] argues that the "second generation" robot will be an embodiement of "firm automation" or more towards the center of the automation spectrum, rather than the truly general purpose, flexible robot. This argument is based on the premise that good software technology that can integrate advanced sensors with adaptive, real time decision making is quite far away. And in the interim, the most intelligent general purpose robots that are being marketed will not be more useful and cost effective than well designed firm automation systems. This technological question of the appropriate levels of general capabilities versus custom design has important strategic implications, and will be discussed in Section 4.



SPECTRUM OF AUTOMATION TECHNOLOGY

FIGURE 6

It was also shown that since robots are actually built up from discrete components, the modularity and interchangeability of the components is an important technological and strategic issue. It is especially important from the end user's standpoint, for he would presumably prefer a robot to be comprised of the "best" components for his application. It is also very important from certain component manufacturers' standpoints, i.e., gripper manufacturers, actuator manufacturers, and controller manufacturers. These manufacturers would like to have their components be compatible with all types/brands of robots. The need for modularity/interchangeability is magnified by the factory of the future concept, in which many systems will be integrated into a grand network. Thus, modularity is important to the end user and certain manufacturers on a number of levels - software, communications, grippers and sensors. However, it is not clear that such interchangeability is the desire of all robot manufacturers, especially those seeking out positions in the market based on bundled, systems solutions.

It will be the development of component interfacing standards that will accellerate or slow the trend toward component modularity. Currently, standards are being promulgated in only the least controversial and least dynamic technological areas, such as gripper/wrist mechanical interfaces. The relationship of the technological issue of modularity to corporate strategy will also be discussed in Section 4.

3. Robot End Users

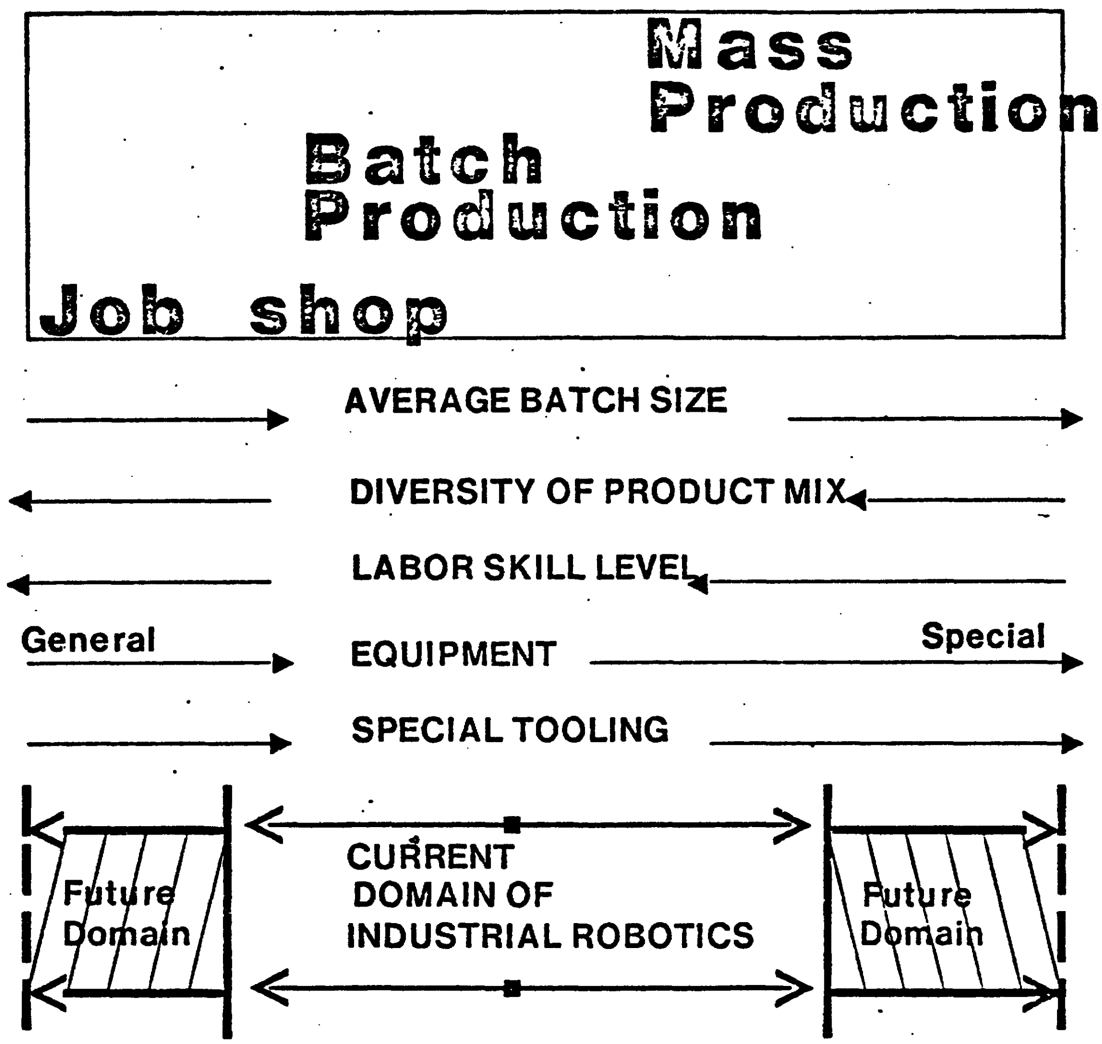
This Section will discuss the applications for individual robots. A key strategic decision for robot manufacturers is which end users to serve, for the potential profitability of a market is very much determined by the leverage that end users have over producers. In addition to outlining and defining the important applications and market segments, this Section will attempt to characterize these segments along such key strategic dimensions as concentration, sophistication, complexity of applications and potential growth. These characterizations will be very important in evaluating the strategies of robot manufacturers and the evolution of their strategies over time.

In examining the many applications that robots are used in, it is important to consider the systems nature of robot use. Robots are usually not stand alone devices. They are most often integrated with other processing or materials handling equipment to form a manufacturing system. In the more mature applications, the system requirements are well understood. However, the complexity of many of the robot applications has given rise to a need for system engineering support for most end users. The robot manufacturer must also determine how much system support to provide as well as which applications to support.

3.1 Applications

Some of the more important applications of robots have already been mentioned in the technology Section. Before discussing these applications in more depth, it is useful to first consider where robots fit into production technologies in a general sense. Figure 7 illustrates a simplified spectrum of production technologies and their important characteristics. The three basic production technologies inlude job shop, batch, and mass production. To date, robots have been most successfully applied in batch processing environments. In this type of environment, the flexible automation embodied in a robot system is an alternative to both labor intensive manual production and capital intensive hard automation systems. The diversity of the product mix and lot sizes in batch production

Comparison of Production Technologies



ADAPTED FROM: Mikell Groover,

Automation, Production Systems, and Computer Aided Manufacturing

Comparison of Production Technologies

FIGURE 7

Source: Ayres & Miller, 1982

justify flexible automation techniques that are simple to reconfigure and do not require extensive customized tooling and engineering. In the future, as robots achieve an advanced level of sensory and decision making capabilities, they will find increasing use in the more highly skilled and labor intensive small lot size environment of the job shop. In addition, as the integration of robots into flexible assembly systems becomes better understood, robot based automation systems will be an alternative to custom engineered hard automation systems in the mass production environment.

FIGURE 8

ROBOT APPLICATONS

I. Point-to-Point Pick and Place Applications

- materials handling (i.e., palletizing, packaging)
- machine tool loading/unloading
- forging and heat treating
- foundry (die and investment casting)
- press loading/unloading

II. Assembly

- electronic component insertion
- integrated circuit assembly
- small parts assembly

III. Processing

- spot welding
- arc welding
- painting
- machining (deburring, drilling, polishing, grinding)
- inspection (measuring)

FIGURE 9

ESTIMATED U.S. ROBOT SALES BY APPLICATION

	Through 1981	1990
Pick and place	25-30%	30-35%
Assembly	10%	35-40%
Spot welding	35-40%	5%
Arc welding	5-10%	15-20%
Painting/finishing	8-12%	5%
Other	8-10%	7-10%

Source: Gevarter, 1982

Robot applications can be thought of in three basic categories. These categories are: pick and place, assembly, and processing. Figure 8 lists the most well known applicaltions in these three categories. Figure 9 shows a breakdown of current and forecasted robot sales by these applications.

3.2 Pick and Place

The simplest of the three categories can be termed pick and place applications. In these tasks, the robot grasps the work piece and relocates it. Such applications include loading and unloading machine tools, conveyor belts, and drop forges, as well as packaging. Because of the simple motions required in most point-to-point applications non servo as well as servo controlled robots are used. They generally have limited sensing capabilities, though electro optical parts presence sensing is often used. However, vision systems are expected to play a big role in point-to-point applications by circumventing the need for extensive parts presentation and fixturing equipment.

Pick and place tasks, specifically press loading/unloading, were the first robot applications. Today, these applications account for anywhere between 30% to 40% of current robot sales [20]. Their share of future robot sales is expected to increase slightly over time, in part due to the increased flexibility these systems will have through the use of vision systems. The jobs that pick and place robots perform are usually tedious and often dangerous for human workers. For example, in the forging and casting applications, the robot functions in a hot, smoky, dangerous environment. In many machine loading/unloading applications, robot systems have been found to be low cost alternatives to custom engineered hard automation systems. Pick and place robot systems are generally the least expensive of the three types of applications. The average cost of such systems ranges from $75,000.00 for materials handling to $100,000.00 for machine loading/unloading [39]. The limited use of sensors and end effector tooling keeps the cost of accessories down in pick and place applications. However, these systems must be integrated with other parts handling or processing machines. This results in significant installation and engineering costs, especially for machine loading/unloading tasks in which control of the robot must be closely coordinated with control of the processing machinery. See Figure 10 for a cost breakdown of the different types of robot systems.

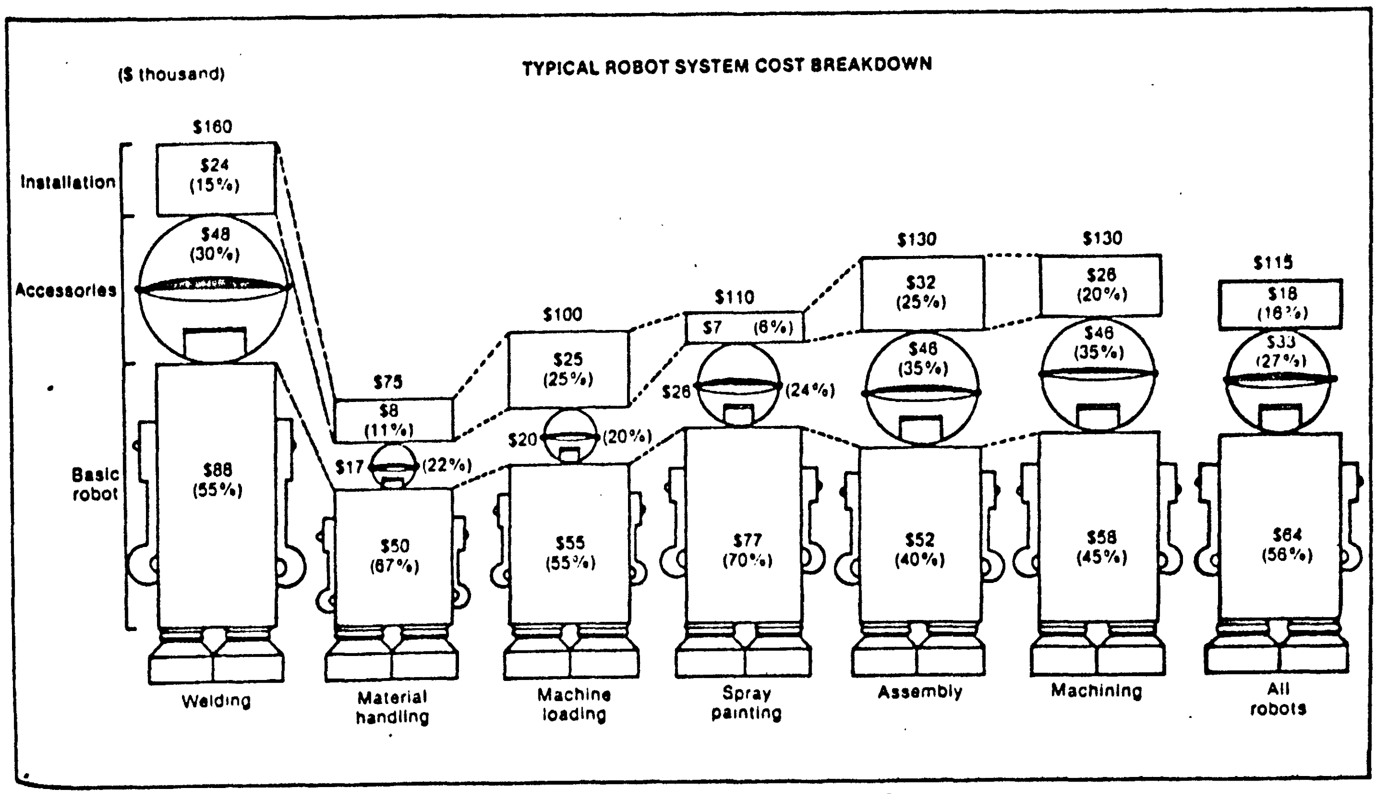


FIGURE 10

TYPICAL ROBOT SYSTEM COST BREAKDOWN

Source: Mini-Micro Systems, April, 1982

3.3 Assembly

Assembly tasks are among the most complex and sophisticated of the robot applications. They are fundamentally similar to pick and place tasks in that the robot grasps the work piece and manipulates it some way. However, the motions required to assemble an object are generally complex, and often require force, vision, and tactile feedback to complete a task and verify that it was done correctly. In addition, assembly tasks require greater accuracy and repeatability than do simple pick and place robot systems. Because of this need for a high degree of control, servo robots with path control are usually used for assembly tasks.

However, there are few assembly robots as we've defined them in actual production today. Assembly applications are said to account for between 5% to 10% of current robot sales, although many of these robots may be performing very simple tasks closer to our definition of material handling [20]. Assembly is expected to become one of the most important applications, accounting for as much as 35% to 40% of robot sales in 1990 [20]. This growth is contingent on the technological developments outlined in Section 2, most notably control and sensor processing software. The complex, general purpose assembly robots will be used to replace manual labor in job and batch production environments. In mass production processes, simpler robots will be integrated witlh programmable parts handling and fixturing equipment to form adaptable programmable assembly systems (APAS). The APAS as well as other types of "firm" automation is expected to be a low cost, flexible alternative to custom designed hard automation systems. Assembly is expected to become the biggest application in the electrical/electronic and light manufacturing industries, and the second biggest application in the automotive industry.

Assembly robots are among the most expensive of the robot systems. A typical assembly robot system costs approximately $130,000.00 including accessories and installation [39]. Sophisticated sensing and control equipment account for as much as 35% of the total system cost. In addition, the assembly robot is usually part of a larger assembly system, resulting in very high (25%) installation and engineering costs.

3.4 Processing

The third category of robot tasks includes all applications in which the robot physically processes the fixtured work piece using a tool attached to the robot arm. These applications include spray painting, welding, and machining. Most processing applications require servo, path control. Arc welding systems often require a vision capability in order to track the weld seam. In processing applications such as machining (drilling, grinding, deburring) in which the tool physically contacts the work piece, force feedback is an important component of control. Such applications present more difficult control software problems than do the welding and painting applications in which the robot arm does not physically contact the work piece.

Processing robots account for between 50% to 60% of current robot sales [20]. In fact, it was the application of robots to spot welding in automobile manufacturing that really stimulated interest in robots in the 1970's. In addition, demand for sophisticated arc welding and machining robots is expected to grow faster than demand for spot welding and painting robots. Processing robots share of the market will decline as assembly robots become more important.

Processing robots replace labor in semi to high skilled applications. However, their real advantage lies in the repeatability and consistency of their motion relative to human motion. In spot welding, for example, robots actually weld slower than men. However, less welds need to be specified since it can be assured that all welds will be performed with predictable high quality. Arc welding robots can be more productive than human welders not because they are faster, but because the torch can be kept on continuously whereas a human welder must stop to rest. In addition, robots can function in hostile spray painting and finishing environments that present severe health hazards to workers. They also offer first cost and flexibility advantages to hard automation processing systems.

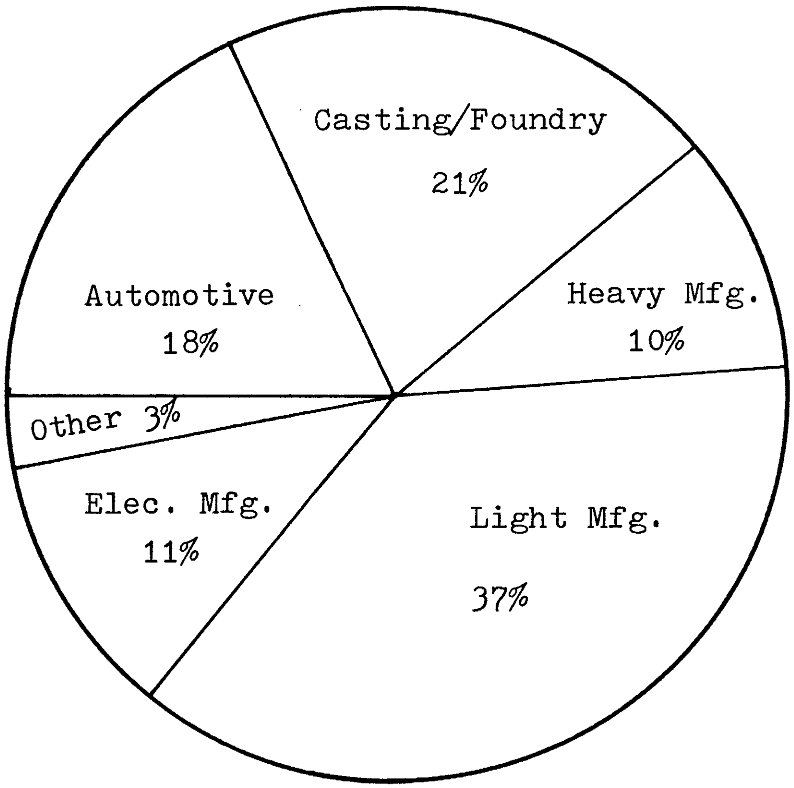
Because of the need for complex tooling and path control, processing robots are generally more expensive than assembly and point-to-point robots. Costs of such systems range from $110,000.00 for a typical spray painting systems to $160,000.00 for welding robots[39]. Tooling costs run as much as 35% of system cost. Installation and engineering is not as costly as in assembly or machine loading, since procesing robots generally require less integration with other factory equipment.

3.5 User Industries

The diverse range of applications in which robots can be used has resulted in their adoption by a number of industries. Figure 11 shows the percentage shares of each of the five major robot using industries in 1979, and a projection of the breakdown for 1985. Of these five industries, only the automative industry is characterized by a small number of very large firms. The other industries are comprised of a large number of firms. Note that according to the projection, only the automative industry will grow in relative share. It is expected that other industries not presently using robots will begin to do so when robots acquire more sophisticated capabilities. Other industries that are expected to be important include aerospace, textiles, chemicals, and agriculture. However, of the expected 47% growth between 1979 and 1985 shipments, 70% is expected to come from the five major industries, and 30% from new applications in other industries[4].

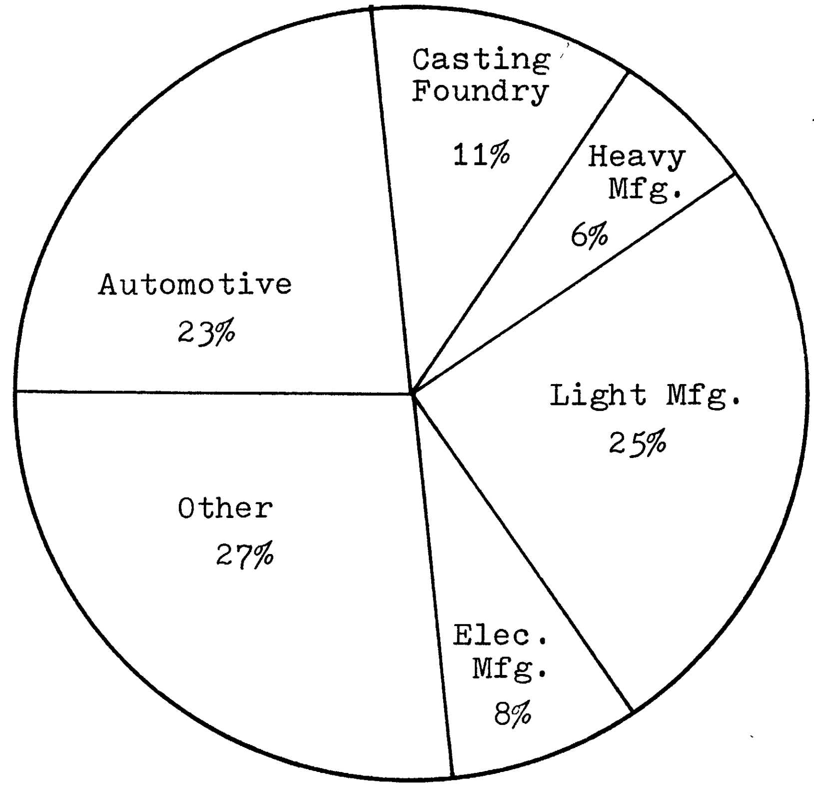
3.6 End User Justification for Robots

A number of surveys have been undertaken in order to better understand the rationales for purchasing robot systems. The results of a Carnegie-Mellon study in 1981 are presented in Figure 12 [1]. Reduction of direct labor costs is by far the



1979

Total U.S. Shipments, 1400 units



1985

Total U.S. Shipments, 8000 units

BREAKDOWN OF ROBOT USING INDUSTRIES

FIGURE 11

Source: Smith & Wilson, <u>Industrial Robots: A Delphi Forecast of Markets and Technology</u>

greatest motivation for purchasing robot systems. The survey results also showed that direct labor savings and the resulting R.O.I. drive the decision to implement a typical robot. Users have a difficult time quantifying the benefit of increased flexibility or improved product quality.

However, this survey aggregated all robot users regardless of application. Clearly, the potential application should have an impact on the users' motivation for puchasing a robot. The Delpi study examined factors affecting purchase decisions as a function of application. These results showed that in processing applications, reduced manufacturing's costs resulting from material savings and better yields outweighed direct labor savings [4]. In addition, the study forecasts that motivation for using robots will change over time, with an emphasis on manufacturing cost reductions other than direct labor, and on enhanced product quality.

RANK	USERS	PROSPECTIVE USERS
1	Reduced Labor Cost	Reduced Labor Cost
2	Elimination of Dangerous Jobs	Improved Product Quality
3	Increased Output Rate	Elimination of Dangerous Jobs
4	Improved Product Quality	Increased Output Rate
5	Increased Product Flexibility	Increased Product Flexibility
6	Reduced Materials Waste	Reduced Materials Waste
7	Compliance With OSHA Regs	Compliance with OSHA Regs
8	Reduced Labor Turnover	Reduced Labor Turnover
9	Reduced Capital Cost	Reduced Capital Cost

Other factors mentioned:

- To give an image of innovativeness.
- To keep up with the Japanese.

FIGURE 12

MOTIVATIONS FOR USING ROBOTS

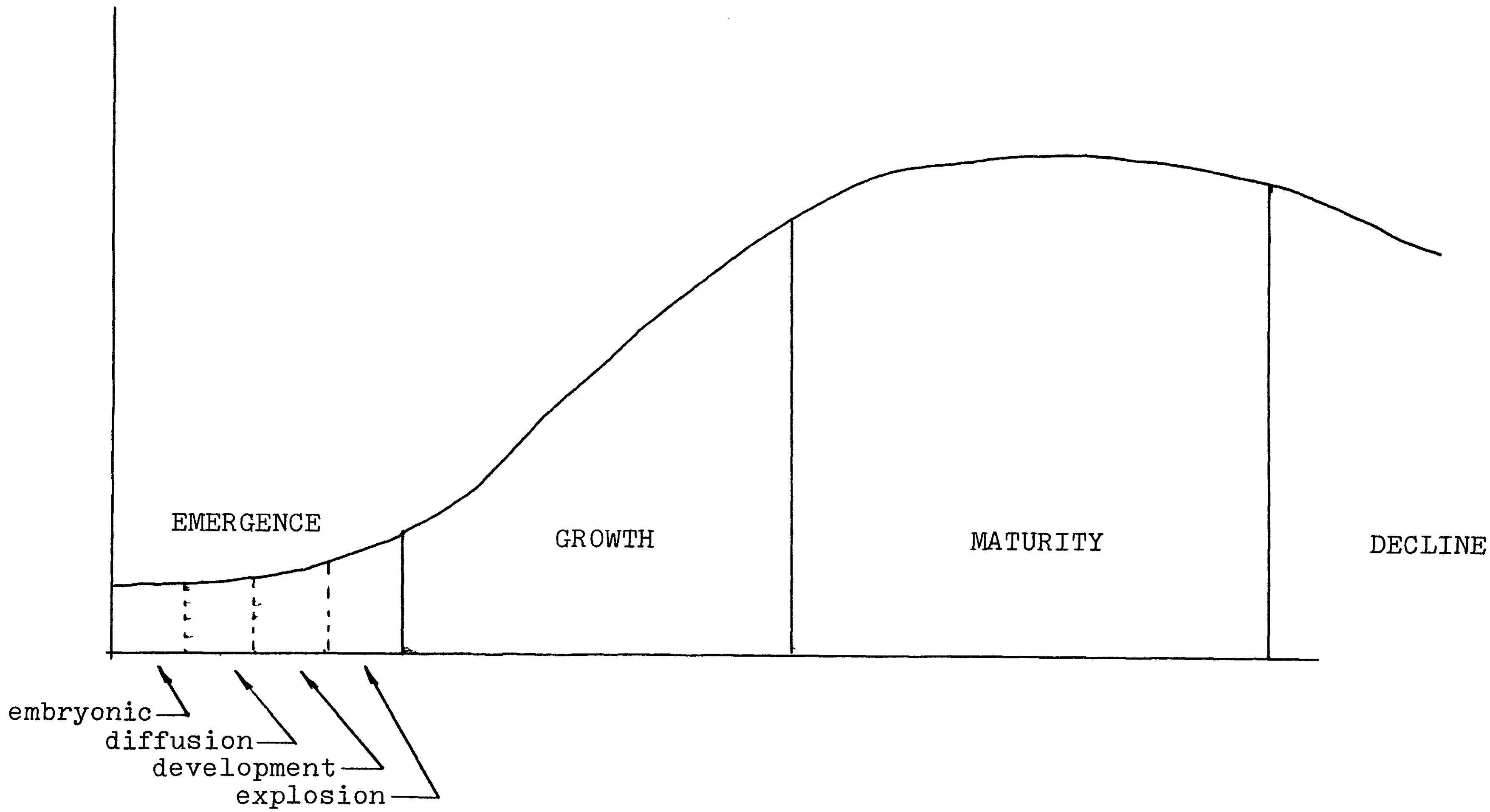
Source: Ayres & Miller, 1982

4. The Robotics Industry

The previous two Sections have attempted to present a rich picture of robot technology and applications. Having this technological and market focus, we can better understand the evolution of the robotics industry and the behavior of robot manufacturers. This Section will begin with a descriptive sketch of the robot industry's twenty-five year life, introducing the actors and the projections for growth in the future. Four distinct stages in the young life of the industry will emerge, and will be discussed in detail. We will then discuss competition and strategy in the industry as a response to industry structure, technology, and the goals of firms involved in the industry. The Section will conclude with a discussion of the future of the industry.

4.1 History of the Robotics Industry

The robotics industry is generally considered to be in the "emerging" stage of the classical industry life cycle. However, much interesting history is lost by condensing the industry's twenty-five year history into a single evolutionary stage. There have been four distinct periods of industry history that are characterized by very different technological and strategic phenomena. These stages are the "embryonic", "initial diffusion", "developmental", and "explosion." They will each be examined in the following sections.



DEVELOPMENT OF THE ROBOT INDUSTRY

FIGURE 13

These four stages emerge from the history because they are empirically distinct and different. Upon further examination, these empirical differences reflect structural changes that occurred in the industry. These changes have strategic importance if they affect industry competition in a fundamental way [12]. The discussion of the four stages will attempt to explain the evolutionary processes at work, and the impact of these changes on industry structure.

4.2 "Embryonic" Stage

Preceding the development of what are considered to be the first robots in 1959, a great deal of the technological groundwork for industrial automation was being done in the aerospace, machine tool, and nuclear power industries. Many of the fundamental component technologies that were outlined in Section 2 were developed in these industries. Servo control technology, especially as applied to hydraulic systems, was being driven by the aerospace industry and its need for sophisticated jet engine controls. Industrial cranes and spray painting equipment are early examples of applications for jointed mechanical manipulators. Manipulator technology was being refined for the handling of radioactive materials in power plant and laboratory environments. These systems, commonly called tele-operators, were really the first application for remotely controlled (though not necessarily programmable), very precise manipulators. Numerical controls were being developed for machine tools through Air Force sponsored research and development. Computer technology was being adapted to replace conventional manual or mechanical control of machine tools. This represented one of the first examples of a flexible, easily reprogrammable industrial machine. Although computer technology was not applied to robot systems until the 70's, flexible automation was first embodied in the development of numerically controlled machine tools.

Credit for the initial "invention" of a robot system is usually given to George Devol and Joseph Engelberger. In 1954, Devol received a patent for his "Programmable Article Transfer Device" - a robot with point-to-point control and an electronic playback memory (hardwired relay logic rather than computer memory). Engelberger managed a small Connecticut based aerospace controls manufacturer, and together with Devol, began experimenting with the concepts embodied in Devol's patents. In 1958, Engelberger's aerospace operation and Devol's patents were acquired by Consolidated Diesel Electric (now CONDEC

Corporation), a manufacturer of military vehicles. It was at Consolidated in 1959 that the first prototype "Unimate" robot was built, and then subsequently installed at General Motors' Turnstead plant. At nearly the same time, in Lansing, Michigan, the Planet Corporation developed and produced a simple, mechanical cam controlled pick and place robot. However, Planet, a material handling systems manufacturer, soon dropped out of robot production, only to re-enter the market in 1980 with its Armax Robot.

The very first "Unimate" was a hydraulic, servo controlled robot with a hardwired electronic memory. It was used to load and unload a hot die casting machine. In developing the Unimate, Devol and Engelberger worked very closely with engineers at GM and Ford to understand their needs and to establish meaningful specifications for the system. The first production Unimate was shipped to a Ford plant in 1961. Consolidated Diesel soon realized that the robot operation would require substantial research and development funding, far greater than it could generate by itself. Its search for a partner to share the burden and risk of such funding ended with an agreement with Pullman Corporation in 1961. Unimation was founded as a joint venture between Pullman (51%) and Consolidated (49%) in 1962.

The seemingly huge market for robots attracted a few other entrants in the early 1960's. American Metal Foundries (AMF) introduced a line of analog controlled pick and place robots. However, they were unsuccessful and subsequently sold the technology to Prab Conveyors in 1969. PaR Systems was started by engineers from the machinery design group at General Mills. Rather than addressing the metal working and automotive industries, PaR developed a line of remotely controlled tele-operators for the nuclear power industry. PaR Systems was acquired by GCA Corporation in 1981.

It was in these early years that Unimation established itself as the industry leader - and, in fact, Unimation was "the robotics industry" throughout most of the 1960's. It also became clear that industry was not prepared to quickly gobble up thousands of programmable, general purpose machines. Unimation found it necessary to customize machines and provide a great deal of applications support. Sales in the years 1962 through 1967 ranged from ten to 50 systems per year. As the pioneer in this emerging industry, Unimation operated at a loss until 1975. Unwilling to continue supporting Unimation, Pullman Corporation sold their interest in Unimation to Condec in the early 1970's. Unimation was recently acquired from

Condec by Westinghouse. The more recent history of Unimation will be explored in later sections.

There are a number of important factors that characterize this embryonic stage of industry development. The driving force behind the creation of this industry was technological innovation. However, the innovation was not one of an academic, scientific nature, but rather one of an engineering, applications oriented nature. The first robot was a synthesis of existing component technologies into a single system. Furthermore, it can be argued that the economically important innovation was finding an appropriate application for this system, rather than the development of the system itself. The relative importance of applications engineering versus product engineering was established early on in the industry's history, and continues to be an important characteristic of the industry.

Because of the engineering/applications nature of the initial innovation, the academic and theoretical work in robotics has anteceded the industrial application of the technology. This application of technology before the theoretical groundwork has been laid is not unusual or unprecedented [3]. Heat engines, telephones and light bulbs were developed before the underlying theory was understood. However, this pattern of innovation is changing as our technology becomes so advanced. Major technological breakthroughs of far reaching economic and theoretical importance now come almost exclusively from the research lab, be it academic, government or industrial.

The nature and role of end users also emerged during the industry's first few years, and set a pattern that continues today. The automotive industry, along with the allied metal working industry quickly became the robot manufacturers' primary customer base. These engineering intensive, sophisticated end users had a very big influence on initial product development and on the identification of new applications for robots. Their sophistication and market power allowed them to shape Unimation, and thus the robot industry, into a responsive, "systems engineering house." In this respect, the robot industry can be compared to the machine tool industry. With machine tools, users have driven innovation by creating new needs and applications, and often by developing and specifying products on their own [13]. This pattern of innovation has steered the development of the machine tool industry towards one characterized by relatively small, custom oriented manufacturers with resulting high production and engineering costs - and low profits [13]. The lethargic, conservative machine tool industry might not seem to be similar to the more dynamic, "high tech" robot industry. However, the pattern of innovation and dependence on end users in the early robot industry is strikingly similar to that of the machine tool industry.

It is also important to note the structure of the automotive industry and its impact on robot manufacturers. The "big three" United States auto makers have traditionally wielded a great deal of power over suppliers. They can use their size and threat of backward integration to drive down suppliers' prices and margins. In addition, the cyclicality of their business presents cash flow and production problems to suppliers dependent on auto makers. The early robot makers' other customer base, the casting and foundry industry is much less concentrated than the automotive industry. Thus, it has less leverage over it. However, much of their business is automotive, or industrial durable related, and subject to the vagaries of the business cycle. The infant robot industry's fate was very much tied to these cyclical and relatively concentrated customer bases.

The concept of industrial of robots has always stirred interest and excitement, if not controversy. The intuitive appeal of flexible automation to the engineers' fancy, and the seemingly huge market for robotic devices attracted a number of entrants to the embryonic industry. However, the goals and motivations of these entrants were quite varied. Unimation, AMF and Planet were horizontal entries from related industries. Of these, AMF and Planet were basically machinery manufacturers seeking to leverage their machine design experience and diversify their existing business. When it became clear that the market for robots was not about to explode, and that it might be many years before a profit could be made, these firms dropped out of the industry and returned to their original lines of business. PaR Systems was an entrepreneurial start up that chose to exploit a single market niche. They, too, sought to apply their mechanical machine design experience in this new marketplace. PaR survived primarily because of their judicious choice of markets, and of course, their ability to execute their market strategy. Unimation's goals and motivation were quite different. At first glance, it may appear that they sought to simply leverage their controls and servo system expertise in a new market. However, it is clear that Engelberger and Devol were, and still are, "true believers" in flexible automation. They survived in the early years through their ability to identify good appications and to work with end users in implementing systems. Above and beyond their abilities as engineers and marketers, it was Engelberger's and Devol's perserverence in the face of over fifteen consecutive losing years that allows it to be the market leader today. This perserverence was the direct result of the founders' total personal commitment to the ideology and technology embodied in robotics. Thus, rather than simply to apply their existing expertise in a new market, Unimation's motivation was the realization of its founders' "Brave New World" of flexible automation. This personal and ideological motivation has enabled the firm to survive through four corporate parents and a decade and a half of unprofitability.

Summary

Many of the forces that have continued to shape the robotics industry emerged in this embryonic stage of development. The industry's technological roots can be traced to the aerospace and nuclear power industries as well as to the general functional discipline of machinery design. Thus, the robot manufacturer became an "integrator" of a set of component technologies. The economically important innovations in this stage of development were the identification of appropriate applications for this technology, rather than general product or component innovations. Furthermore, the industrial application of "flexible automation" preceeded any academic research or theoretical development. The robot industry's first cusomer base was a concentrated and powerful one - the automobile manufacturers. However, it was also a sophisticated and innovative one. End users initially played and continue to play a big role in the identification of new applications and the specification of system capabilities. The early promise of the robot industry in part rested on this relationship with a huge, capital intensive customer base. This promise attracted a number of early entrants. The unprofitable and uncertain nature of the market for robots soon drove out most of the entrants, and left Unimation as the sole supplier of industrial robots. Unimation's staying power can be atrributed to the personal and ideological commitment of its founders.

4.3 Diffusion Stage

The period beginning about 1965-1966 and ending 1970-1971, can be thought of as a diffusion stage. It was a period in which a worldwide technological "intfrastructure" began to be built. However, it was not characterized by dynamic market activity. Industry sales were miniscule, on the order of $1 million per year (20 units), and were almost totally accounted for by Unimation[54]. The unprofitability and uncertain demand of the earlier years continued, discouraging the entrance of any new players into the market. Quite simply, the point-to-point, hard wired controlled robot had limited market appeal. Automotive and metal working firms continued to be the primary customers, using the robots to replace manual labor in hot, dangerous and dirty work environments. The United States robot "population" was estimated to be only 200 in early 1970 [1].

Despite the lethargic market performance during this stage, there were many evolutionary forces at work. Academic research into robotics was initiated in the mid 1960's in the United States and United Kingdom. Robotics research labs were established at M.I.T., Stanford, Stanford Research Institute, and the University of Edinborough. It was in these academic environments that computer control was first applied to robotic manipulators. By 1971, researchers had successfully implemented mini computer based control, making use of simple force and tactile sensory feedback. Work was beginning on vision systems, and the development of programming languages for real time, feedback control of manipulators. In 1970, the first International Symposium on Industrial Robots was held, representing the academic "coming of age" of robot technology.

Although the impact of this research on commercially available robots would not be felt until the early mid "1970's," the application of computer technology to robotics held far reaching consequences for the industry. Unimation, with its mechanically oriented technology, was not in a position to quickly develop commercialized computer based control systems. The application, or "invation" of this new technology would create a new path, or "technological track" for entrants into the robotics industry. In fact, the first manufacturer to commercialize a computer controlled robot was Cincinnati Millicron. They leveraged their technologic expertise gained in the development of computer controlled machine tools. Millicron and the commercialization of computer controlled robots will be discussed further in the next Section. However, it is clear that the technological invation of computer technology had far reaching structural and strategic impacts on the industry. The groundwork for these changes was laid in the research lab in the late 1960's.

The establishment of a robotics research center in the United Kingdom represented the first international diffusion of robotic technology. However, diffusion of an economic and strategically important nature did not occur until 1967. As a guest of the Japanese government, Joseph Engelberger toured Japanese factories and was given the opportunity to preach the robotic "gospel."

The concept of flexible automation was enthusiastically received. Quoting Engelberger:

> "The Japanese were predisposed to robots... They had a fascination with new technology and they were convinced that with zero population growth and a monolithic society that imported no labor, they'd soon run out of workers"[27].

Although it is a bit dramatic, Engelberger's assessment is quite valid. The Japanese had already been using pneumatic, non servo controlled manipulators as building blocks for hard automation systems. Consequently, the robotic technology that Engelberger proposed was not quite as alien and mysterious to the Japanese. Furthermore, the concern over possible labor shortages was very real. Thus, the Japanese were indeed more predisposed to robots than were the Americans or Europeans. In 1968, Unimation signed a licensing agreement with Kawasaki Heavy Industries, giving Kawasaki the exclusive manufacturing and marketing rights to the Unimate line of robots. Since then, the implementation of robots in Japan has far outpaced that of the United States. The reasons for this, as well as alricher description of the Japanese robot industry will be presented in subsequent sections.

The diffusion of robot technology to Japan has had a number of structural and strategic implications. A new, receptive customer base had been identified creating an opportunity for growth in the industry. In fact, Engelberger was forced to go to Japan in search of growth opportunities because of the very limited and increasingly saturated demand for robots in the United States. Unimation's small size and limited resources prevented it from entering the Japanese market directly. Its choice of licensing as a means of addressing world markets set a pattern that continues today. Firms having a technological strength and seeking to exploit international markets look to the licensing arrangement as a low cost, low risk means of establishing an "instant" manufacturing and distribution system. Licensing has become a very important strategy in the robot industry, and will be discussed at length in Section 4.5.

In addition to simply broadening and internationalizing the industry, the diffusion of robots to Japan has had a more far reaching consequence. The adoption of robot technology, as well as of statistical quality control and numerous other Western innovations helped the Japanese establish the manufacturing superiority that they enjoy today. In an effort to catch up with the Japanese, American and European companies are now scrambling to "robotize" and automate their plants. As a consequence of its early internationalization, the robot industry is now able to take advantage of international competitive forces in user industries as a means of stimulating demand for robots.

The early adoption of robot technology by the Japanese has important implications for the theories of international trade. Traditional theory holds that due to the United State's historical technological and industrial lead over the rest of the world, product innovations are likely to first be developed and take hold here, then are exported to other industrial countries and finally to less developed countries. Furthermore, the innovations of firms in a given country are thought to reflect the needs and characteristics of that given market United States firms have produced products that address labor saving or high income needs. European and Japanese firms produced products and innovations that address capital and material saving needs. In addition, the Japanese are known for "space" saving innovations, given the crowded nature of their country.[103] Intuition would therefore lead us to believe that given our technological advancement and high labor costs resulting in the need for productivity increasing innovations, the United States should have been the "ripest" market for the robot industry. Indeed, that the initial innovation took place in the United States is consistent with the theory. However, the technology caught on much quicker in Japan. This experience underscores the weakness of traditional international trade theory given the technological advancement and changing markets throughout the world.

In discussing the embryonic stage of the industry's history, it was shown that the important initial innovation was of more of an applications nature than of product nature. Another very important "applications innovation" occurred in 1968. While designing and outfitting their new Lordsform plant, General Motors called on Unimation to develop a robotic spot welding system. This represented the first use of a robot in a processing application. Spot welding soon became one of the most important robot applications, and in doing so, further cemented the robot manufacturers' ties with the automotive industry. The use of robots for processing a work piece greatly expanded the market beyond the traditional pick and place applications. In addition, it created the opportunity for firms having processing expertise (i.e., spray painting, welding) to become involved in the robotics industry. An example of this was the joint development of the early spot welding systems by Unimation and Linde Welding Systems. They have subsequently cooperated on the development of arc and gantry welding systems. Note that these types of working relationships not only allow the parties access to each other's technologies, but also to each other's distribution channels. The melding of processing technology with robotic technology stimulated a number of interesting licensing arrangements and joint ventures that will be discussed in the next few sections.

The only significant new entrant into the United States robotics industry during this period was Prab Conveyors. A small Michigan manufacturer of materials handling and conveying equipment, Prab acquired the Versatran line of non servo robots from AMF in 1969. They have since improved and expanded the product line with non servo robots of their own design. By concentrating on simple, reliable non servo technology, Prab has been able to become the leader in the non servo, pick and place niche. Prab's success is evidence of the demand for simple robots with technology appropriate to the task at hand. Auto Place, Inc. was a Michigan based start up that also began offering a line of non servo, pick and place robots in 1969. However, unlike Prab, Auto Place did not provide a high level of customer service and support. Consequently, they did not enjoy the same success as Prab, and were acquired by Copperweld in 1979. The experience of Prab and Auto Place stimulated the entry of other firms into the non servo market in the early 1970's. These firms will be discussed in the next Section. The segmentation of the robot market by Prab and Auto Place, and their technological strategy in addressing that segment was an important development in the history of the robot industry.

Summary

The "diffusion" stage of development in the robot industry was not characterized by dynamic market activity. The industry continued to be dominated by Unimation. The most important development was the diffusion of robot technology into the university, and to international markets. Academic research into robotics centered on the application of computer control of robots. Such research was clearly beyond the capabilities of the mechanically oriented robot manufacturers of the day. It will become evident in the next few sections that the use of computers vastly expanded the usefulness and applicability of industrial robots. In addition, it created opportunities for firms with computer control expertise to enter the market.

The diffusion of robot technology to Japan was initiated by Unimation's licensing of Kawasaki Heavy Industries in 1968.

Demand for industrial robots in Japan soon outpaced that in the United States. The growth of the Japanese robot industry will be outlined in the next Section. In addition to providing a new market for United States robot technology (and later a source of technology), the diffusion to Japan has had a longer term effect on the industry. The use of robots was a key element of their strategy for achieving manufacturing superiority. Western countries now find themselves having to "catch up" with Japanese manufacturing methods and are robotizing their own factories at an ever increasing rate.

This stage also saw the development of the first processing applications for robots. The use of robots for spot welding broadened the market for robots, and created an opportunity for firms with processing technology to become involved in the robot industry. This new application was another example of innovation by customers rather than by the robot manufacturer.

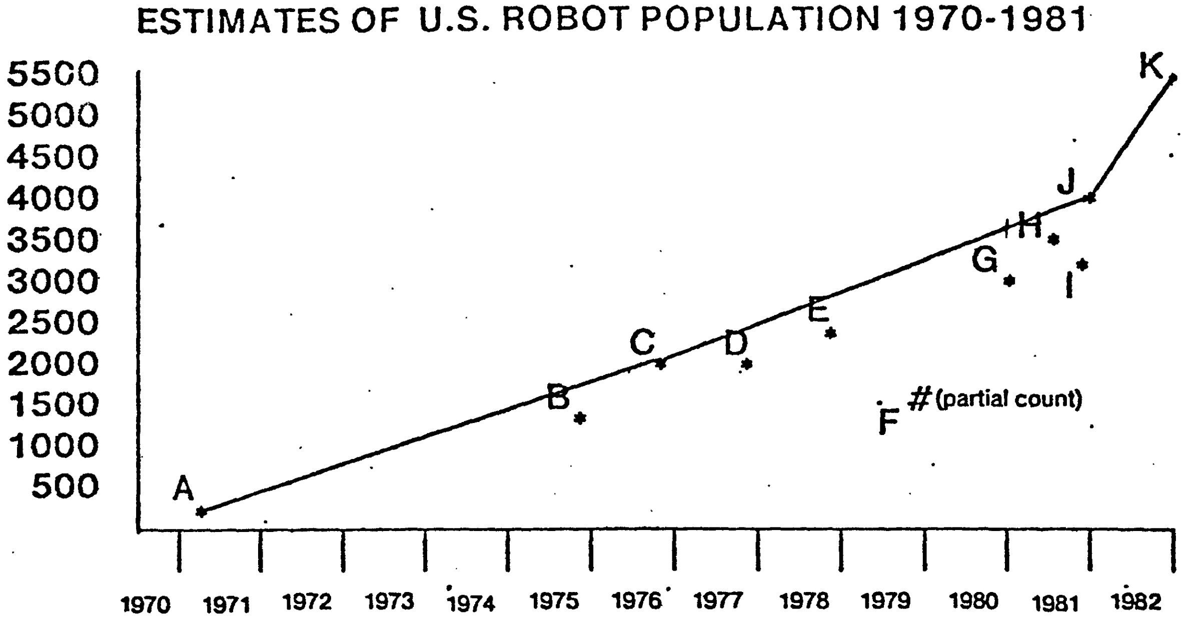
The only new entrants into the robot industry were Prab Conveyors and Auto Place, Inc. These manufacturers both chose to address the non servo segment of the market. Their strategy was to compete with Unimation by offering cost effective, simple and reliable non servo systems for appropriate pick and place applications.

The relatively weak demand for robots and Unimation's continued unprofitability served to discourage entry of more firms into the industry. In 1970, only "true believers" like Joseph Engelberger were confident that the robot industry would prove to be viable and profitable.

4.4 Technological Development Stage

The 1970's saw considerable growth in demand for and sales of industrial robots. Industry sales increased from $6 million in 1970 to $90 million in 1980, representing an approximately tenfold real increase in sales. On a unit basis, sales increased from 100-200 units in 1970 to approximately 1,000 units in 1980 [54]. Estimates of the United States robot population for 1970-1981 appear in Figure 14. This growth served to legitimize the industry and created opportunities and incentives for a number of firms to enter the industry. The industry did remain very concentrated, with two firms accounting for seventy (75%) percent of sales in 1980 Unimation continued to dominate the market, holding a forty (40%) percent share in 1980 [17]. Figure 15 illustrates the changes in industry sales and market share for this stage in the industry's development. Note the trend towards decreasing concentration as more firms entered the industry in the 1970's. It is difficult to evaluate the profitability of the industry, since most of the players have other important product lines. This decade saw the first profits, albeit small ones, made in the robot industry.

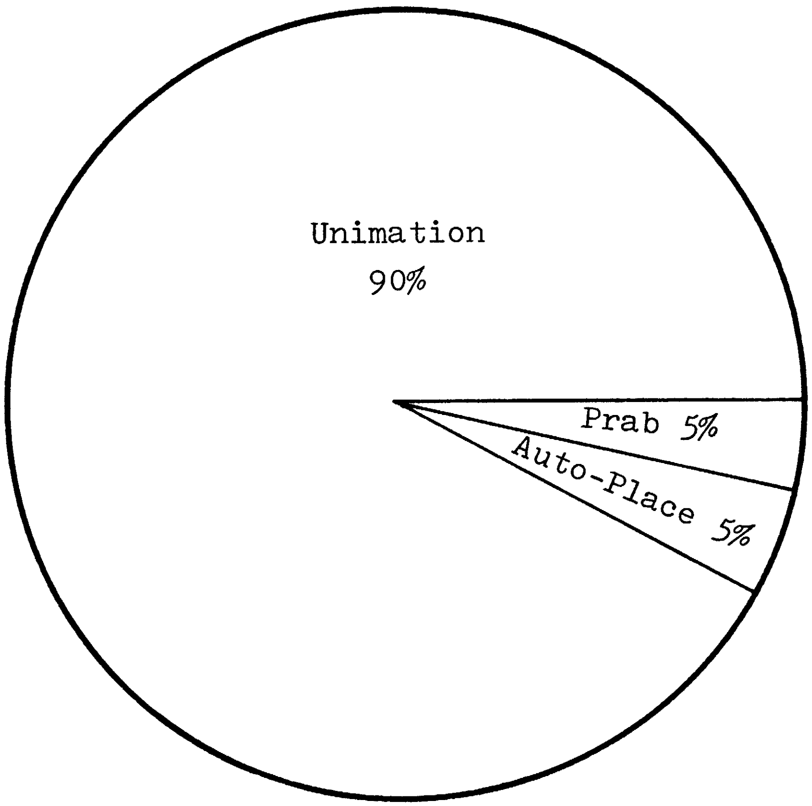
The real story of this stage is not simply industry growth or profitability, for even at $90 million in annual sales, it was a "lilliputian" market. Driving the growth in demand was the commercialization of research and development work initiated in the mid-1960's and described in the previous Section. These



Point	# of Robots	Date	Source
A	200	1970 (April)	Engelberger, First National Symposium on Industrial Robots , 1970
B	1200	1974 (Dec.)	Frost and Sullivan, U.S. Industrial Robot Market, 1974
C	2000	1975 (Dec.)	Frost and Sullivan, The Industrial Robot Market in Europe, 1975
D	2000	1976 (Dec.)	Eikonix Technology Assessment, 1979
E	2400	1977 (Dec.)	Eikonix Technology Assessment, 1979
F	1600	1978 (Dec.)	American Machinist 12th Inventory, 1978
G	3000	1980 (Jan.)	Walt Weisel, Prab Conveyors
H	3500	1980 (June)	Business Week, Verfied by Cincinnati Milacron
I	3200	1980 (Dec.)	General Motors Technical Staff, (Bache,Shields estimate)
J	4000	1980 (Dec.)	Walt Weisel, Prab Conveyors
K	5500	1981 (Dec)	Seiko Inc., Marketing Dept.

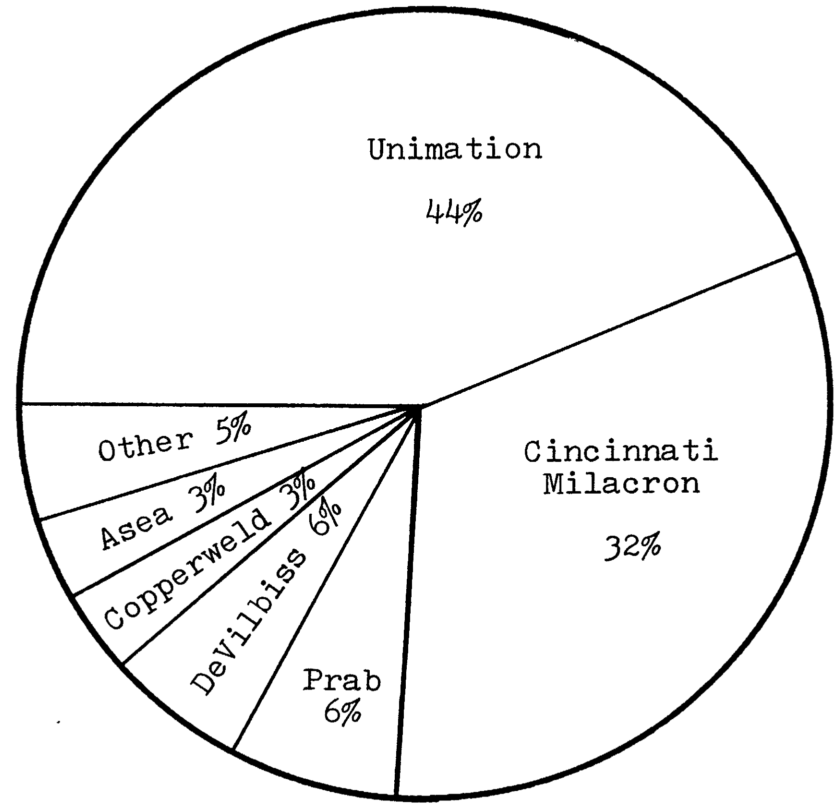
FIGURE 14

Source: Ayres & Miller, 1982



1970

U.S. SALES, $6 MILLION*



1980

U.S. SALES, $90 MILLION

INDUSTRY SALES AND MARKET SHARE

FIGURE 15

*Estimated

Source: Conigliaro, 1982

technological developments and the resulting strategic implications will be discussed in this Section. In addition, the continuing importance of processing applications, niching strategies, and the international market will be examined.

The application of computers and microprocessors to robot control was the most important technological and market development of the 1970's. In 1973, Cincinnati-Milacron, then the leading United States producer of machine tools, introduced the first mini-computer controlled robot, the T3. Milacron drew on its expertise gained in the development of computer controlled machine tools. It was able to develop the hydraulically driven, articulated T3 entirely in-house. This servo controlled robot was designed for heavy duty pick and place applications and for processing tasks such as spot welding and machining. In addition, the T3 was designed for use as a machine tool loader/unloader, and as such, can be integrated with other Milacron machine tools to form automated machining cells. Milacron was able to successfully leverage its existing technological expertise in machine design and computer control, as well as its established channels of distribution. By 1980, it had become the number two robot manufacturer in the United States, with $29 million in sales and a thirty-two (32%) percent market share [17]. It used a strategy of product differentiation, namely the increased flexibility afforded by the computer control and by the articulated arm to successfully challenge Unimation in the very same markets and applications that were Unimation's strength.

Milacron was not the only company to introduce computer controlled systems. Ollivetti (Italy) introduced a mini-computer controlled robot in 1974, although it has never been marketed in the United States. ASEA, a Swedish company, introduced a microprocessor controlled robot in 1977, and began marketing it in the United States in 1979. The Unimation experience in bringing a computer controlled robot to market is an interesting example of the diffusion of technology from the academic research lab to the marketplace. In 1974, Victor Scheinman established Vicarm Corporation in order to commercialize his innovative robotic technology developed as a researcher at Stanford and M.I.T. The Vicarm robot was a small, electrically driven, articulated arm controlled first by a mini-computer, then later by a microprocessor. To control the Vicarm, Scheinman adapted the programming language "AL", which he helped to develop while at Stanford.

The Vicarm robot was designed to handle light payloads in complex parts handling and assembly applications. The company was established in

Mountain View, California, far from the traditional robot markets of the industrial mid west and north east, but right in the heart of the booming, high tech Silicon Valley. Despite Scheinman's advanced technology, the young company experienced financial difficulties. At the same time, Unimation was working closely with General Motors on the specification of a "Programmable Universal Machine for Assembly," dubbed the PUMA. The PUMA was to be designed for light assembly and parts handling applications. Seeing the natural fit of Scheinman's technology with the specifications for the PUMA, Unimation acquired Vicarm in 1977. They subsequently won the bid for manufacture of the PUMA and were able to adapt the Vicarm design to the PUMA specifications. The existing Vicarm organization in Mountain View became Unimation West - and provided Unimation with the computer control expertise it sorely needed to compete with Milacron. The first PUMA was shipped to GM in 1978, and the robot has since become a standard for light assembly and parts handling applications. Unimation has been able to apply the microprocessor control techniques and software developed for the PUMA to its existing line of Unimate Robots.

Underlying the Unimation experience with the PUMA are two very important forces. First, it became clear that sophistication and expertise with computer technology would be a prerequisite for survival and growth in the robotics industry. No longer would simple machine design expertise be enough of a technological base for entry and success into the industry. In fact, as early as 1970, IBM began developing in-house robotics technology drawing primarily on its software expertise. The commercialization of computer controlled robots not only stimulated market demand, but also changed the rules for who could become a robot manufacturer. Secondly, the PUMA was another example of user based innovation. From the original Unimate, to the spot welding application, to the specification of the PUMA, end users (specifically General Motors) have played a leading role in technological innovation.

Another example of diffusion from the research lab to the market was the establishment of Machine Intelligence Corporation (M.I.C.) in 1977. M.I.C. commercialized a vision system based on algorithms for pattern recognition developed at the Stanford Research Institute. M.I.C. worked with Unimation to integrate its vision module with a PUMA robot, and such a system was first offered in 1980. Since then, M.I.C. has entered into a joint venture with a Japanese robot manufacturer to supply vision equipped robot systems. Vision has now become another technological track for entry into the robot industry.

This stage of the robot industry's history also saw the growing importance of processing applications for robots, and the resulting strategic responses. In 1972, DeVillbiss offered the first continuous path, servo controlled robot designed for spray painting applications. DeVillbiss was a leading supplier of industrial spray painting equipment. A subsidiary of Champion Spark Plugs and an important supplier to the automobile industry, DeVillbiss was very much aware of the robot's capabilities and acceptance among auto makers. However, rather than developing the robot in-house, DeVillbiss chose to license robot technology from Trallfa, a Norwegian robot manufacturer. Since 1972, DeVillbiss has had exclusive worldwide marketing rights (except for Scandinavia and Japan) for Trallfa robots. In 1981, it was also given exclusive North American manufacturing rights. Previous to 1981, DeVillbiss acted as an original equipment manufacturer, purchasing Trallfa robots and integrating them with their own spray painting equipment, and marketing the system under the DeVillbiss name. This strategy allowed DeVillbiss to enter the robotics market with little initial investment, and enabled it to take advantage of its existing distribution network and strong relationship with the automobile industry. Choosing to work with Trallfa rather than with Unimation or one of the other United States manufacturers was a key strategic decision for DeVillbiss. DeVillbiss was able to offer to Trallfa, an existing distribution network, as well as its spray painting technology. Presumably, Trallfa would be willing to "pay" for the use of DeVillbiss' marketing system in the form of lower prices. A United States robot manufcturer would already have existing distribution channels, and would presumably not be willing to recompense DeVillbiss for the use of theirs. Thus, DeVillbiss could realize better margins by importing robot technology than by working with a United States manufacturer. In addition, it is not clear that Unimation or Prab, the only United States firms offering servo controlled robots, were willing to enter into an O.E.M. arrangement with DeVillbiss. By 1980, DeVillbiss had become the leader in the continuous path segment of the market, realizing sales of $5 milliion and capturing approximately 5.5 percent of the total market [17]. It has adapted its basic robot for other continuous path applications, but focuses primarily on spray painting.

DeVillbiss was not the only company to enter the robot industry in the early "70's" with a "niching" strategy. Following the non servo niching strategies of Prab and Auto Place, Industrial

Automates and Mobot entered the market in 1973 and 1974, respectively. Industrial Automates produces an inexpensive ($12,000.00) robot designed for injection molding and parts handling applications. However, their product is felt to be technologically inferior to the non servo robots offered by Prab, Auto Place, and Mobot [53]. As a result, Industrial Automates has achieved limited market success. Mobot (formerly Modular Machine Company) has pursued a unique product strategy. Rather than marketing a fully specified system, Mobot offers a line of modular manipulators and drive systems. The customer can build up a complete robot system, having only the necessary degrees of freedom and the most appropriate drive system for the application. To date, Mobot systems have been used primarily in pick and place operations. However, given their modular design, they can be equipped with the necessary instrumentation and control system to provide servo control, and could be used in more complex applications. The founder of Mobot, Lawrence Kamm, believes that most robot manufacturers and end users are suffering from a "Pygmalion" mind set, and have unnecessarily complicated robot systems by trying to emulate human architecture and motion [31]. Despite Mobot's flexibility and cost advantages over competing systems, the company achieved sales of only $800,000.00 in 1980, and has yet to earn a profit. Due to the Company's small size it is unable to provide extensive engineering support to end users. It must rely on having customers sophisticated enough (and willing) to invest their own engineering in integrating and specifying a system. However, given the relatively short history of robot technology, and the unfamiliarity of most customers with it, Mobot has had difficulty selling the concept of user integrated, modular robots. Perhaps when end users have accumulated a base of experience with robot technology, they will have the sophistication and desire to specify customized systems built up from modular components. This pattern of design is typical of many engineering disciplines in large companies, especially those disciplines that are the most technologically mature. Mobot's strategy may be a sound one, albeit a decade ahead of its time.

From 1974 to 1979, there were no significant new entrants into the industry. This lull in activity can certainly be blamed in part on the recession of 1974-1975 and the generally poor performance of the automobile industry, the robot industry's most important customer base. In addition, the high interest rates that characterized the latter half of the 1970's discouraged investment in new technology.

However, 1979 and 1980 saw the entry of a number of new firms into the United States robot market. All of these firms market systems that address processing applications, although their strategies are quite different and reflect the changing nature of the robotics industry.

Nordson Corporation is a manufacturer of industrial spray painting, packaging and hard automation equipment. In 1979, they introduced a spray painting robot of their own design. Leveraging their internal spray painting and automation expertise, as well as their established channels of distribution, Nordson realized sales of nearly $1 million in 1980, and is now second to DeVillbiss in the spray painting market [17]. Nordson has recently entered into an agreement with Yaskawa of Japan to distribute Yaskawa's robots designed for finishing applications such as sealing, caulking, and applying adhesives. The agreement also calls for technology sharing between the two firms. Binks, a British manufacturer entered the United States market in 1979 with a similar strategy. However, due to its technological inferiority compared to the DeVillbiss and Nordson systems, as well as its undeveloped marketing channels, Binks has met with little success [53]. Thermwood Corpration was a manufacturer of plastic molding machinery. In 1980, it introduced a line of robots including two designed for injection molding and other point-to-point applications. It also introduced a continuous path spray painting robot. Thermwood is the first United States robot manufacturer to pursue private label marketing arrangements. It now supplies Binks with its Model Six spray painting robot which Binks remarkets under its own name. Thermwood also has an agreement with Cyclomatic Industries, Inc., to produce precision arc welding robots under the Cyclomatic name. Cyclomatic will sell and service the Thermwood built robot worldwide. In 1982, Thermwood reached a similar agreement with Didde Graphics Systems Corporation to produce a materials handling robot modified for graphic arts applications. Ken Susnjara, Thermwood's president, hopes to establish at least 10-12 of these private label marketing agreements [28]. Advanced Robotics Corporation, an Ohio based start up, introduced a line of sophisticated welding robots in 1979. It has also pursued the private label strategy in addition to marketing its own line of robots. The company reached an agreement with Metallurgical Industries, a manufacturer of plasma wear surfacing and arc welding equipment, to produce systems under the Metallurgical name. This unique strategy relfects the importance of established distribution channels and applications experience.

Automatix Inc. entered the industry in 1980. Their entry is of particular significance for a number of reasons. Automatix was the first robot manufacturer to originate from a computer systems technological base, rather than from a mechanical machine design or processing technology base. Their founders come primarily from Computervision Corporation, a leading CAD/CAM manufacturer. Victor Scheinman, whose contributions at Vicarm and Unimation were discussed previously in this Section, was also among the founders. The company markets a line of vision systems, welding robots and assembly robots. Its technological strategy has been to develop superior vision, control systems and programming languages in-house, and to license robot arm technology from Hitachi of Japan. Automatix has a close working relationship with Lincoln Welding Systems, who provides arc welding equipment for its robots.

The company has positioned itself as "the robotic systems company." As such, it concentrates on just a few applications and provides extensive applications engineering support to customers. The turnkey system marketing approach is felt to be necessary because of the unfamiliarity of most first time purchasers with robot technology, and the need to establish the fledgling company as a legitimate and reliable alternative to the more experienced robot manufacturers [49]. This strategy is very similar to Computervision's CAD/CAM system marketing strategy. In addition, because of many of the founders' experience in the CAD/CAM industry, Automatix is very sensitive to and well prepared to address the problem of integrating robot systems with CAD/CAM or other factory automation systems.

Automatix' strategy of licensing proven robot arm technology is evidence that an efficient, competitive market for relatively simple and mature arm technology has now developed. As the analysis of component technologies in Section 2 illustrated, there is now much more opportunity to stake out a proprietary market position based on software, vision and controller technology than on manipulator or drive technology.

The 1970's saw the rapid growth and development of the Japanese robot industry. Estimates of the robot "population" of Japan in 1980 ranged from 11,000 to 14,000, about three times the estimated robot population of the United States [1],[20]. The well developed robot industry in Japan is important not only because it provides opportunities and threates to the United States industry, but also because it can serve as model for what the United States robot industry might look like when it achieves an equivalent size.

Following an early boom in robot sales soon after their introduction to Japan in 1967-1968, the demand for robots "fizzled" much as it did in the United States after introduction in the early 1960's. It was only after the "oil shock" of 1972-1973 that the robot industry achieved significant growth. The effect of the oil shock on the Japanese industrial and economic psyche is well documented. It reinforced the strategic goal of achieving worldwide superiority in manufacturing a broad range of industrial and consumer products. In addition, it stimulated investment in productivity improving and cost reducing technologies such as robotics. Coupled with their natural "predisposition" to robot technology outlined in the previous Section, the oil shock provided the impetus for the rapid adoption of robot technology.[5] The Unimation licensee, Kawasaki Heavy Industries, become the market leader in Japan. However, a large number of companies soon entered the market. Many of these were large companies that saw involvement in robotics to be important not only because of market opportunities, but also because of their need to develop in-house robotics expertise. Such companies include Hitachi, Fujitsu Fanuc, Nippon Electric and Matsushita for all of whom robotics represents a miniscule percentage of their total sales. The industry has evolved to where there are now over 145 Japanese firms producing or developing robot technology, compared to the estimated totals of 55 United States firms and 75 European firms.[29] Industry sales reached $314 million in 1980, although included in this figure are many of the simpler manipulators not considered to be "robots" in the R.I.A. definition [29]. More importantly, Kawasaki's market share has been reduced to about 6.5 percent in 1981. Entrants into the industry have succeeded by carving out niches - offering robots designed for specific applications and with varying levels of technological sophistication. Many user firms have forward integrated into the manufacture and marketing of robot systems developed for in-house use. Furthermore, not all of these are the high technology or heavy industry firms mentioned above. Sailor Pen and Pentel market robot systems they developed for in-house injection molding and assembly applications.

The importance of the end user in identifying applications for robot technology and actually implementing them is underscored by the Japanese experience. United States observers of the Japanese robot industry like to point out our technological superiority in software and computer control technology. However, it has been shown that applications experience and innovation have been more economically significant than purely technological innovation. The Japanese robot industry has become less unconcentrated because of entering firms' abilities to exploit specific applications. Applications expertise has proven to be more important than robotic product expertise because of the relatively simple technology embodied in current robot systems. The implications for the potential profitability of the robot industry is clear. The low technological barriers to entry and resulting high number of firms will cause any excess profits to be competed away. While the potential for growth in sales in the industry is tremendous, it is not clear that the Japanese robot manufacturer will be unusually profitable.

The Japanese government has played an important role in the growth of the robotic industry. In addition to helping articulate a general industrial strategy, the Ministry of International Trade and Industry (MITI) has promoted a great deal of robotics research and development. In 1980, MITI sponsored a program of tax incentives for purchases of robot systems. In addition, it arranged for the creation of Japan Robot Leasing Corporation, a joint venture of 24 Japanese robot manufacturers and 10 insurance companies. The leasing company offers subsidized, long-term robot leases to smaller firms that would otherwise be unable to purchase robot systems. The involvement of MITI in the robotics industry gives rise to

United States manufacturers' anxieties about having to compete with "Japan, Inc." The competitive threat that Japanese robot manufacturers pose to United States firms, as well as the opportunities that the well developed market in Japan offers, will be discussed in the next Section.

Summary

The United States robot industry grew from $6 million in 1970 to $90 million in 1980. In addition, this decade saw the first, albeit small, profits made on the sale of industrial robots. As important as the growth in sales were the commercialization of several new technologies. This decade saw the introduction of computer and microprocessor based control systems, the articulated arm, and vision systems. The strategic implications of these technological innovations is that there are now many new paths for entry into this industry. Cincinnati Milacron based its early entry on expertise gained in the development of computer controlled machine tools. Machine Intelligence and Automatix have used vision and computer systems technology as a basis for entering the industry. Seeing the growing importance of computer technology, Unimation acquired Vicarm in 1977 and has since marketed the computer controlled PUMA as well as offering computer based control systems for its Unimate line of robots.

Parallelling the diffusion of computer technology into robotics was the growth in importance of processing applications. This phenomenon also created a new path for entry into the robotics industry. DeVillbiss and Nordson were manufacturers of spray painting equipment that saw the opportunity to leverage existing channels of distribution and technological expertise by marketing spray painting robots.

The entry of all the firms discussed in this Section are evidence of low barriers to entry in the robot industry. An efficient, international market was developing for the individual component technologies. Firms such as Automatix and DeVillbiss could simply go overseas to license proven, mature arm and drive technology. In addition, firms such as Thermwood and Advanced Robotics market robot systems on a private label basis. This provides the opportunity for processing technology companies to offer robot systems without having to develop robot manipulators of their own. The lack of mechanical manipulator design expertise is simply no longer a barrier to entry in the industry. The ability of foreign and domestic robot producers to align themselves with processing technology companies effectively eliminates the lack of established channels of distribution as a barrier to entry. In addition, it provides robot manufacturers with "instant" applications experience. Such experience has been shown to be as important, if not more important, than experience with the robot technology itself.

The effect of these low barriers to entry will presumably be the entry of a large number of firms. We might also expect to see normal, rather than excess profitability. Indeed, the Japanese experience confirms this expectation. The rapid growth in the industry attracted many entrants. The relatively low technological and marketing barriers to entry have enabled the new entrants to reduce Kawasaki Heavy Industries leading market share to about 6.5 percent.

4.5 Explosion Stage

The last few years (c. 1980 - present) can be characterized as a stage of industry "explosion." Sales of United States robot manufacturers increased from $90 million in 1980 to over $180 million in 1982, with predictions of between $225 million and $275 million for 1983, depending on the strength of the economic recovery [19],[32]. Figure 16 illustrates two forecasts of robot industry sales. Partly as a result of this growth, and certainly in part a stimulus for it, was the tremendous mass media, academic and investment interest in the robot industry. Industrial robots, dubbed the "steel collar" work force, are now looked upon as a key element in reviving the United States' industrial competitiveness.

In addition to growth in industry demand, the past few years have seen the entry of upwards of 50 firms involved in some aspect of the robot industry. Looking at a chronology of entry into the industry (see Figure 17), it appears that some "threshold" was reached in 1980-1981, opening the floodgates for a large number of new firms. The entry of a diverse array of firms has resulted in a very rich spectrum of strategies. In addition, it has resulted in decreasing concentration. The four firm concentration ratio (CR4) decreased from .88 in 1980 to .67 in 1982, and can be expected to decrease to further, because of the low barriers to entry and mobility in the industry.

The recent entrants to the industry include venture capitalized start ups as well as established multi-national corporations from a number of technological tracks. Their motivations and strategies for entering the industry are as diverse as their

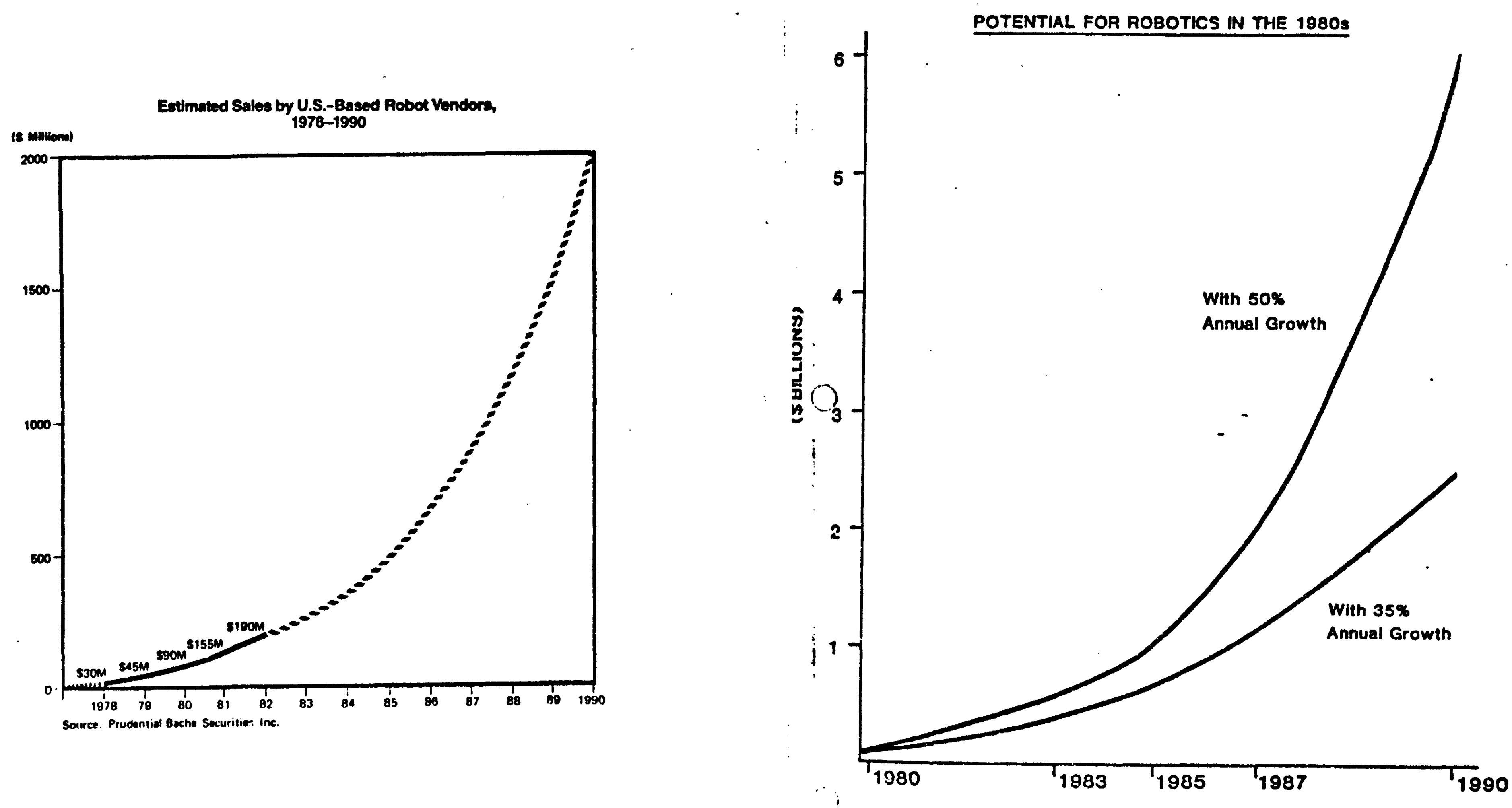


FIGURE 16

FORECASTS OF ROBOT SALES

Sources: Conigliaro, The Yankee Group

FIGURE 17

CHRONOLOGY OF ENTRANCE INTO THE ROBOT INDUSTRY

Year	Firm
1959	Condec Corp. Planet Corp.
1962	Unimation A.M.F. PaR Systems
1969	Prab Conveyors, Inc. Auto-Place
1972	Devillbiss
1973	Industrial Automates
1974	Cincinnati Milacron Mobot
1979	ASEA Binks Nordson Advanced Robotics Corp.
1980	Thermwood Automatix
1982	General Electric Westinghouse I.B.M. Bendix General Motors-Fanuc G.C.A Graco Cybotech Admiral Products Control Automation U.S. Robots
1983	Textron United Technologies Nova Robotics Intelledex Machine Intelligence Lloyd Tool and Mfg.

Market Share: U.S.-Based Robot Vendors*

(1980 - 1983)

	1980	1981	1982	1983
Unimation	44.4%	43.8%	32.1%	22.8%
Cincinnati Milacron	32.2%	32.2%	21.0%	16.2%
DeVilbiss	5.5%	4.2%	7.4%	6.7%
Asea Inc.	2.8%	5.8%	6.7%	7.2%
Prab Robots Inc.	6.1%	5.3%	4.2%	4.2%
Cybotech	-	-	4.9%	4.2%
Copperweld Robotics	3.3%	2.3%	2.3%	1.8%
Automatix	0.4%	1.9%	4.2%	7.6%
Advanced Robotics Corp.	1.9%	0.5%	3.5%	3.2%
Nordson	0.8%	1.6%	2.5%	2.5%
Thermwood	-	0.6%	1.6%	1.4%
Bendix	-	-	1.4%	2.3%
GCA Industrial Systems	-	-	1.0%	2.9%
IBM	-	-	0.7%	3.0%
GE	-	-	0.9%	1.1%
Westinghouse	-	-	0.4%	1.5%
U.S. Robots	-	-	0.6%	1.5%
Graco	-	-	0.6%	1.1%
Mobot	0.9%	0.4%	0.8%	0.8%
GM/Fanuc	-	-	1.5%	3.0%
American Robot	-	-	-	0.6%
Textron	-	-	-	0.3%
Nova Robotics	-	-	-	0.3%
Control Automation	-	-	0.1%	0.3%
Machine Intelligence	-	-	-	1.1%
Intelledex	-	-	-	0.6%
Other	1.7%	1.3%	1.5%	1.7%
	100.0%	100.0%	100.0%	100.0%

FIGURE 17a

Source: Conigliaro, 1982

individual corporate histories and personalities. Upon first examination, it seems that the entry of so many firms in such a short period can be explained as a rational, economic response to the industry's recent growth and the optomistic forecasts for future growth. In addition, the 20 years of experience accumulated by the pioneers in the industry served to reduce the uncertainty surrounding the demand and technology, thus, justifying the entry of the larger and more risk averse companies. However, we must also be cognizant of less purely rational, political motivations. Remember that Unimation's persistence can be explained as much by the ideology and personal commitment of its founders as by their purely rational, economic motivation.

1982 and 1983 saw the entry of several very large firms including IBM, General Motors, General Electric, Westinghouse, Bendiz, United Technologies, and Textron. Their motivation for entry can, in part, be attributed to the desire to leverage existing marketing channels, technological expertise, and product lines. The diversity of these firms' technological tracks underscores the diverse nature of the robotic component technologies, and the wide range of opportunities that this diversity creates. Figure 18 lists the technological backgrounds of most of these horizontal entrants as well as of

FIRM	AUTOMATED MACHINERY	MACHINE TOOLS	SPRAY PAINTING	AEROSPACE	AUTOMOTIVE	ELEC. EQUIP.	COMPUTERS	OTHER
Unimation	X			X				
Planet	X							
A.M.F.	X							foundry
PaR	X							
Prab	X							
Auto-Place	X							
DeVilbiss			X					
Industrial Auto.	X							
Mobot	X							
ASEA						X		controls
Binks			X					
Nordson	X		X					
Thermwood	X							
Automatix							X	
General Elec.				X		X		
Westinghouse				X		X		
I.B.M.							X	
Bendix		X			X			
Cincinnati Milacron		X						
GMF		X			X			
G.C.A.								semicond. equip.
Graco	X							
Cybotech			X		X			
Admiral Products								weld. equip.
Textron		X		X				
United Technologies				X	X	X	X	
Intelledex							X	
Machine Intelligence							X	vision equip.

TECHNOLOGICAL BACKGROUNDS OF ENTRANTS

FIGURE 18

the more noteworthy start ups. For many of the larger entrants, the robot industry is yet another battleground on which to combat historical competitors. General Electric and Westinghouse have long competed in industrial and consumer markets, and the robot industry represents a logical extension of their historical competition. Similarly, Textron and Bendix have long competed with each other (and Cincinnati Milacron) in the machine tool industry, and now face each other in the robotics industry. Therefore, participation in the robot market can be thought of as part of these firms' overall corporate strategies for competing with historical adversaries in an effort to prevent competitors from gaining a strategic advantage. Quite simply, firms see competitors entering an industry, and then feel it necessary to enter so as to not "miss the boat." Such an explanation is appealing because it helps explain the coincidental timing of the entry of so many firms.

In Section 2, the concept of "factory of the future" (F.O.F.) was explained. Participation in the robot market can be though of as one element of these larger firms' strategies for involvement in the broadly defined F.O.F. market. In recent years, General Electric has acquired Calma, a CAD/CAM company, and Intersil, a manufacturer of networking and communications equipment. Robots are another piece of the F.O.F. puzzle for

General Electric, rather than simply an effort to address a specific and growing market. Similarly, IBM has participated in CAD/CAM and communications markets. It must see its participation in the robot as not only a means to sell control computers and robot arms, but also to establish an early presence in the F.O.F. market [50]. Having been beaten to the mini computer market by DEC and to the office automation market by Wang, IBM is taking swift action so as to not be left out of the factory automation market. The other large firms that entered the industry in 1982-1983 also clearly have designs on the broadly defined factory of the future, rather than just the robot market.

Another important motivation for these large, diversified manufacturing firms to enter the robot industry is their desire to gain in-house experience with robotic technology as well as to leverage their existing robotics applications experience. Firms such as IBM, General Motors, Bendix and General Electric have almost as much (if not more) to gain by robotizing and automating their own operations as they do in marketing robots to other companies. The experience of Japanese manufacturing companies that use robots diversifying into producing robots reiterates the importance of applications expertise to success in the robot market. Participation in an external robot market affords these firms an opportunity to commercialize technology developed for internal needs. Furthermore, their applications experience with the technology places them at an advantage relative to firms that only produce and market robot technology.

In addition to the numerous large and medium sized companies that have diversified into robotics, a number of start-up firms have entered the market. For the most part, their motivation has been to take advantage of existing manufacturers' unfamiliarity with, and inability to adopt, state of the art computer control and vision technology. These firms generally address the more complex applications, ones that the more mechanically oriented producers have been slow to pursue. However, in addition to the entrepreneurial motivation to exploit opportunities that existing producers cannot or do not address, the ready availability of venture capital and general investment interest in the robotics industry has stimulated the formation of robotic start ups. For most of the existing robot manufacturers, as well as for all the larger recent entrants, robot sales represent a small fraction of their total corporate business. The opportunity for investors to capitalize on growth in the robot industry is diluted by these firms' business diversification. Thus, there has been tremendous interest in the robotics "pure play" - the opportunity to invest in a robot company unburdened by other lines of business. Prab Robots (formerly Prab Conveyors) went public in 1981 and was rewarded with a P/E multiple of 36.5, based on 1982 earnings [24]. Automatix, Inc. went public in early 1983. It was able to issue 1,150,000 shares at $19.00 per share, netting the company over $20 million. At the time of the issue, Automatix had not yet recorded a profit, and does not expect one until late 1983 [49]. Such tremendous investment interest has undoubtedly stimulated the formation of start up companies. One might expect such strong stock market appeal to also attract "marginal" types looking to "get rich quick." Indeed, there have been a few start ups whose products have been designed more for stock market appeal rather than to address real market needs.

Nearly all of the recent entries, including start-ups and large corporations have made use of some form of interfirm relationship. Relationships range from marketing and manufacturing licensing agreements, to shared equity joint ventures, to outright acquisitions and mergers. Figure 19 enumerates the more important interfirm relationships that have been struck in recent years. The spate of these relationships is indicative of the diversity of component technologies, and of the international nature of the industry. The motivation to pursue such relationships based on the fact that they allow the

FIGURE 19

INTERFIRM RELATIONSHIPS

LICENSING AGREEMENTS

Licensee	Licensor
Kawasaki Heavy Ind.(Japan)	Unimation
FN Eurobotics(Belgium)	Prab
Can-Eng Mfg.(Canada)	"
Murata Machinery(Japan)	"
Binks(U.K.)	Thermwood
Cyclomatic Ind.	"
Didde Graphics Co.	"
DeVilbiss	Trallfa(Norway)
Nordson	Yaskawa(Japan)
Admiral Equip. Co.	"
Bendix	"
Automatix	Hitachi(Japan)
General Electric	"
Interrad	"
Graco	Molaug(Norway)
United Technologies	Nimak(W. Germany)
GCA	Dainichi Kiko(Japan)
I.B.M.	Sankyo Seiki(Japan)
General Electric	DEA(Italy)
" "	Volkswagen(W.Germany)
Westinghouse	Ollivetti(Italy)
"	Misubishi Electric(Japan)
"	Komatsu(Japan)
Lloyd Tool and Mfg.	Jobs Robots(Italy)

JOINT VENTURES

J.V.	Parents
Unimation	Condec, Pullman Corp.
GMF Robotics, Inc.	General Motors, Fujitsu Fanuc
Cybotech	Renault, Randsburg Industries
Int'l Machine Intell.	Machine Intelligence, Yaskawa
Graco Robotics	Graco Inc., Edon Finishing

MERGERS AND ACQUISITIONS

Subsidiary	Parent
Unimation	Westinghouse
PaR Systems	GCA
U.S. Robots	Square D Corp.
Copperweld Robotics (formerly Auto-Place)	Copperweld Corp.

participants to realize technological and/or marketing synergies, and reduce the lead time required to introduce a product.[15] The form of the relationship (i.e., licensing or merger) depends on such elements as transactions costs, efficiency gains, and naturally, the longer term strategies of the participants [15].

Licensing agreements have been the most common form of interfirm activity. Much as DeVillbiss licensed continuous path robot technology from Trallfa of Norway, General Electric, IBM, Westinghouse, United Technologies, and a number of other large companies have licensed robot arm technology from Japanese and European robot manufacturers. The licensing arrangements were, in effect, surrogates for internal research and development. They allowed these firms to come to market quickly with proven robot technology, while they develop their own technology in-house.

The motivation to pursue foreign technology rather than United States technology was explained previously for the DeVillbiss/Trallfa agreement. Quite simply, foreign manufacturers are willing to recompense their United States licensees for "instant" access to United States markets, while a United States robot manufacturer would presumably find much less value added in the relationship. In addition, some of the more advanced Japanese and European manipulator designs are felt to be just as good, if not better, than those of United States robot manufacturers. Refering back to the disucssion of component technologies, it was shown that robot arm technology is among the most mature, and most easily reverse-engineered of the component technologies. It is not clear that internal research and development will at this point enable a firm to produce a signficantly improved robot arm. This technological maturity and efficient international markets have made licensing arrangements a viable option for United States firms seeking to enter the market. In addition to acting as licensees, a few United States firms are licensors of robot technology. Unimation and Prab both have Japanese and European marketing and manufacturing licensees. Other United States firms seeking to export robot technology operate through independent distributors.

The shared equity joint venture is a far more structured and long-term interfirm relationship. Two of the more notable joint ventures have involved automobile manufacturers. GMF Robotics Corporation was formed in June, 1981, as a joint venture between General Motors and Fujitsu Fanuc, a leading Japanese machine tool and robot manufacturer. General Motors brings a tremendous amount of applications experience and internally developed technology to the venture, as well as a large internal (though not captive) market. Fanuc, which had previously sold its robots through a United States licensee, General Numeric, brings a line of proven robot arms and controllers, in addition to its existing machine tool channels of distribution. Cybotech was another venture involving an automobile manufacturer. It was established in 1980 as a joint venture between Renault and Ransburg Corporation, a manufacturer of electrostatic spray painting equipment used primarily in the automobile industry. Similar to General Motors, Renault brought a great deal of applications experience, as well as a line of sophisticated robot systems to the venture. Ransburg, in addition to its spray painting technology, brings a knowledge of the United States market and existing industrial channels of distribution. The motivation for General Motors and Renault to seek such a structured relationship is clear. Neither company has signficant experience in selling expensive, complex systems to industrial customers. The joint venture affords them the opportunity to commercialize internally developed technology without distracting their efforts in their traditional automotive product lines. Another important joint venture was formed by Machine Intelligence Corporation, a supplier of vision systems, and Yaskawa Electric Manufacturing Co., a Japanese heavy equipment and robot producer. International Machine Intelligence Corporation and Japan Machine Intelligence Corporation were founded in the United States and Japan, respectively. These spinoffs will provide sophisticated vision equipped robot systems by drawing on the technological expertise of the two parents. Japan Machine Intelligence will market the full line of Yaskawa robots, the M.I.C. vision system, as well as integrated robot/vision systems. International Machine Intelligence will market only integrated systems, so as to not compete with Yaskawa's other United States licensees. The synergy between these two technologies will place the joint ventures at an advantage to robot firms trying to develop or license vision technology, and vice versa. In addition, by "bundling" their vision system with a robot, M.I. is trying to protect its vision system from becoming a simple, commodity-like module. The joint venture is therefore an attempt by M.I. to increase its own market power. However, it does place M.I. in the position of competing directly with its robot producing customers.

The third important mode of interfirm relationship is the outright acquisition or merger. The most noteworthy of these was the recent acquisition of market leader Unimation by

Westinghouse. Unimation's previous owner, Condec Corporation, had been experiencing financial problems, ending its fiscal year 1982 with a loss of $16.5 million, or $4.17 per share [24]. In addition, its highly leveraged balance sheet and expectations for another losing year in 1983 created a need for an infusion of cash. At the same time, Unimation's needs for research and development funding are increasing as it must keep pace with the advanced technology of its many new competitors. Westinghouse entered the robot market in 1982 with a line of robots licensed from Komatsu and Mitsubishi of Japan, and Ollivetti of Italy. In the continuing struggle between Westinghouse and General Electric, both firms have been looking for a competitive edge, and it is known that both firms were negotiating with Condec [18].

Westinghouse finally did acquire Unimation from Condec in late 1982 for $107 million, of which $83 million went to Condec, and $24 million to the general public at $21.00 per share. The direction and success of "Westimation" is unclear, although the purchase did solve some important problems for all three parties. The infusion of cash to Condec will enable it to retire debt and help it through its current difficulties. Unimation will now have an important source of research and development funding as well as some sorely needed top management personnel. Westinghouse now has access to an existing worldwide customer base using over 5,000 robots and a line of proven, albeit somewhat mature, robot systems. It is expected that Westinghouse will play a much more active role than Condec did, although Unimation will continue to manufacture and market systems under its own name [51]. With its designs on the "factory of the future," Westinghouse is expected to try to assume the role of systems integrator [51]. They will be market systems consisting of Unimation equipment, licensed equipment, and internally developed equipment. The ultimate success of this acquisition will depend on Westinghouse's ability to achieve a degree of control over Unimation's financial and managerial systems, while maintaining and stimulating its technological creativity. However, it is clear that if the acquisition did not occur, Condec, Unimation and Westinghouse would have much poorer chances for success.

The other acquisitions of note involved smaller robot manufacturers. United States Robots was a small start up manufacturer of microprocessor controlled, parts handling and assembly robots. It was acquired in 1982 by Square D Corporation, a manufacturer of industrial controls. PaR Systems, one of the very earliest entries to the industry, was acquired by GCA Corporation in 1982. GCA is a manufacturer of automated semiconductor processing equipment that markets a line of robots licensed from Dainichi Kiko of Japan. PaR Systems, with its reliance on the now stalled nuclear power industry, found itself at somewhat of a crossroads. Funding and technological support from GCA will enable it to apply its teleoperator and manipulator technology to factory automation systems. The motivation for the small robot producers to sell out to larger corporate buyers is rooted a need for financial security, i.e., corporate "deep pockets," and also in the need for managerial direction. The risk of such acquisitions is that the inventors and entrepreneurs of the company might find it difficult to sacrifice their autonomy to the parent company. This desire to maintain autonomy explains the small number of outright acquisitions and mergers relative to licensing and joint venture agreements.

In addition to pursuing an interfirm relationship as a strategy for entering the robot industry, a number of firms have also endeavored to develop robot technology in-house. Textron, Bendix and in the early 1970's, Cincinnati Milacron, all developed their robot technology internally. IBM recently introduced the RS-1, a sophisticated assembly robot that was developed for in-house needs. The RS-1 joins the 7535, a less sophisticated robot licensed from Sankyo Seiki of Japan. Both

General Electric and Westinghouse are pursuing internal development in addition to offering their licensed and acquired lines of robots. An interesting example of the similarity of their strategies and of the nature of competition between them is their establishment of formal ties with university research organizations. In 1979, General Electric founded the "Renssalaer Center for Manufacturing Productivity and Technology Transfer" at Renssalaer Polytechnic Institute. In 1980, Westinghouse founded the "Robotics Institute" at Carnegie Mellon University. Both of these organizations are involved in state of the art automation research, as well as applied research geared to their funders' more immediate needs. The establishment of such university based research arms is a response to General Electric's and Westinghouse's relative unsophistication in advanced computer technologies. They are hoping that this strategy will enable them to be technologically competitive with those firms entering from a computer oriented technology track.

These last few pages have detailed the motivations and strategies for entry into the robot industry by some of the newer participants. The remainder of this Section will examine the spectrum of competitive strategies being pursued by the many firms in the industry. Porter's framework of three generic strategies - focus, differentiation and cost leadership will be used to characterize this broad spectrum of strategies [12].

Focus on particular applications is an important strategy, especially for those smaller firms that have recently entered the somewhat crowded industry. Firms that pursue such a strategy usually have a strong base of experience in that given application, or obtain that experience through some sort of interfirm relationship. The growth in importance of processing applications created market niches for firms having experience with and an existing channel of distribution for processing equipment. Focus on a specific application is effective not only because customers require significant applications support, but also because different applications require different levels of technological sophistication. Companies such as Prab, Mobot and Seiko of Japan focus on simple pick and place applications by offering relatively simple non-servo robots. Most of the newer companies such as Automatix, International Machine Intelligence, and Intelledex focus on complex arc welding and assembly applications by offering much more complex, vision equipped robot systems. At the other extreme of the strategic spectrum are firms that attempt to address a broad range of applications. Such companies include Unimation, ASEA and

Bendix. An additional dimension of focus is the level to which a firm offers specialized machines designed for a given application or general purpose machines adapted for different applications. Figure 20 characterizes robot manufacturers by the number of applications supported. Figure 21 characterizes their product offerings as being general purpose or specialized. A broader measure of a firm's corporate focus is the portion of their annual sales that is robot related. Figure 22 illustrates the spectrum of firms involved in the industry, ranging from dedicated robot manufacturers to diversified, multi-market companies.

Product differentiation is also a very important strategy in the current robot industry. The most common form of product differentiation is the degree of intelligence incorporated in the robot control system and the sophistication of the sensors that are used. The ability to make use of vision is an important differentiating feature. In addition, the quality and user friendliness of programming software, and the ability of robot systems to link to CAD/CAM or other factory computer systems have become important features. To a lesser degree, the choice of arm architecture and drive technology are differentiating features. However, the maturity of these technologies make them relatively less important than control or sensing

FIGURE 20

NUMBER OF APPLICATIONS SUPPORTED

Firm	#	Applications*
ASEA	12	A-E,G-M
Bendix	12	A-E,G-M
Unimation	10	A-E,G,H,J,L,M
Cincinnati Milacron	9	B-E,H-K,M
Copperweld	8	A-E,G-I,L
Cybotech	8	D-H,J-M
Thermwood	7	A,C-F,H,I
Mobot	7	A-F,I
U.S. Robots	6	A,D,E,G,L,M
General Electric	5	F,G,J,L,M
Automatix	4	G,J,L,M
DeVilBiss	4	A,F,H,J
American Robot Corp.	4	E,G,I,L
Nordson	3	F,H,M
Advanced Robotics	2	J,M
Intelledex	2	G,L

*Key

A	Die Casting
B	Forging
C	Investment Casting
D	Machine Tool Load/Unload
E	Parts Transfer
F	Spray Painting
G	Small Parts Assembly
H	Finishing
I	Injection Molding
J	Welding
K	Machining
L	Electronics Assembly
M	Inspection

Source: 1982 Robot Industry Directory

FIGURE 21

SPECIAL PURPOSE VS. GENERAL PURPOSE

Firm	Avg. # of Applications/Model
ASEA	14
Bendix	11.5
Cincinnati Milacron	9
Copperweld	8.3
Mobot	7
Unimation	5.3
American Robot Corp.	4
Cybotech	4
Thermwood	3.7
Nordson	3
DeVilBiss	3
Automatix	2.5
General Electric	2.3
Advanced Robotics Corp.	1.7

Source: 1982 Robot Industry Directory

FIGURE 22

ROBOT SALES AS PERCENT OF TOTAL SALES

	Firm	Robot Sales/Total Sales(%)
GROUP 1 (100%)	Automatix	100
	Prab Robots	100
	Advanced Robotics	100
	Mobot	100
	Intelledex	100
	Control Automation	100
	Nova Robotics	100
GROUP 2 (1%)	ASEA	16.25
	Cybotech[1]	9.5
	Cincinnati Milacron	4.5
	Nordson	3.1
	DeVilBiss	1.8
GROUP 3 (1%)	Graco Robotics	.9
	GCA	.9
	Copperweld Robotics	.8
	Westinghouse[2]	.7
	Textron	*
	GMF Robotics[3]	*
	Bendix	*
	General Electric	*
	I.B.M.	*

* much less than 1%

1-expressed as % of Randsburg's sales

2-includes Unimation sales

3-expressed as % of G.M. sales

equipment as a basis for differention. Another important aspect of technological differentiation is modularity. Most manufacturers offer a degree of component modularity, although Mobot is the only firm to offer truly modular systems that can be configured by choosing the arm, drive, controller, sensors and software appropriate for a specific application. The concept of interchangeability of different manufacturers components has yet to become an important product feature. Indeed, most manufacturers offer "bundled" systems in an effort to prevent the component technologies from becoming true commodities.

Perhaps even more important than technological differentiation is the degree and quality of applications support and follow-up service that a manufacturer provides. Automatix, Westinghouse, and General Electric are examples of firms that provide turnkey system support. They engineer complete systems including the robot arm, controller, end effector and any necessary parts handling and fixturing equipment. Such support is especially important when selling to first time users who are unfamiliar with robot technology. System reliability as measured by "up-time", and service as measured by response time, are also important product features. Prab has been able to achieve leadership in the non-servo segment of the market in part due to its average

98-99% "up time", and less than 24 hour service response [53]. In fact, in a survey of reasons for buying a particular brand of robot, the quality of the service force was most often mentioned as the most significant factor.[53]

The channels through which a manufacturer sells and supports its systems also varies. The companies mentioned above market systems directly, and do the applications engineering in-house. IBM has chosen to sell robots through what it calls "value added remarketers." Commonly referred to as systems houses, these consulting firms provide the necessary applications engineering. However, most systems houses are not contractually tied to just a single robot manufacturer, and as a result, can chose the most appropriate (or most profitable) robot components.

Because of the relatively low production volumes in the robot industry and the need to provide expensive applications support and service, no manufacturer has succeeded in establishing a significant position based primarily on cost leadership. Pricing reflects the level of technological sophistication, i.e., the controls and instrumentation that are included in the system. However, robot manufacturers that produce their own arms presumably operate at cost advantage relative to the firms that must purchase or license a significant component in their system. It is likely that as production volumes increase in response to increased demand, the larger, vertically integrated manufacturers such as Westinghouse/Unimation, Cincinnati Milacron, and GMF will seek positions of cost leadership based on scale and learning effects. The nature of competition in the industry is bound to change as the fixed costs associated with high volume production will make the industry much more price competitive. Figure 23 illustrates the price (not cost) positions of the more important manufacturers.

Summary

The past few years have seen explosive growth in the robot industry, both in industry sales and in the entry of new firms. Industry sales have increased at an average rate of over forty (40%) percent per year since 1980 to reach a level of $185 million in 1982. Sales are forecasted to reach $500 million by 1985 and exceed $1 billion before 1990 [18]. This tremendous growth potential has attracted a large number of entrants with a range of corporate and technological backgrounds. As a result, the industry is becoming less and less concentrated.

FIGURE 23

PRICE POSITIONS

Mid-range system price	Manufacturer(model)
$25,000-$50,00	Unimation (Apprentice)
	Prab (4200,5800)
	Copperweld (all)
	Thermwood (Series 3,7)
	U.S. Robots (all)
	Mobot (all)
$50,000-$100,000	Unimation (Unimate,PUMA)
	Cincinnati Milacron
	ASEA
	Prab (FA,FB)
	Automatix
	Advanced Robotics (750,820)
	Thermwood (Series 6)
	Bendix
	General Electric (P5)
$100,000-$200,000	Advanced Robotics (2000)
	Nordson
	GCA
	General Electric (A12,AW7,S6)
	Prab (FC)
	Cybotech

Source: 1982 Robotics Industry Directory

The motivations for entry of these firms are very diverse. Several large companies (e.g., IBM, General Electric, Westinghouse) have entered the robotics industry as a means of pursuing a strategy for involvement in the broadly defined "factory of the future" market. In addition, the robotics industry is a new battleground for firms that have historically competed with each other in other markets. Many small start up firms have entered the industry. Unburdened by commitments to traditional technologies and customer bases, these start ups seek to exploit niches created by the application of sophisticated vision and control systems. The entry of such firms has been stimulated by a ready supply of venture capital and stock market interest in the robotics "pure play."

The recent entrants have pursued a number of different strategies for entry. Interfirm relationships such as licensing agreements, joint ventures and mergers and acquisitions have all been used effectively. These types of relationships allow the participants to realize technological and marketing synergies, and reduce the lead time required to introduce a product. Most of these arrangements have involved the importation of proven Japanese or European robot technology. In many cases, these relationships are serving to tide the manufacturers over until internally developed systems can be introduced.

The industry is characterized by a rich spectrum of competitive marketing strategies. Focus on specific applications is an effective strategy because of the need for the manufacturer to have and provide considerable applications engineering support. In addition, there are a number of firms that offer systems addressing a broad range of applications. Firms try to differentiate themselves technologically and by the level of systems engineering support they provide. Because of low production volumes, no firm has been able to establish a significant position based on manufacturing cost leadership. However, as sales volume increases, vertically integrated producers will have a significant cost advantage over firms that license or purchase a substantial part of their system.

4.6 Future of the Robotics Industry

Throughout its 25 year history, the robot industry has been characterized by overly optimistic expectations for growth. The intuitive appeal of flexible, easily reprogrammable industrial robots has so far outstripped their actual market appeal. However, the rapid growth of the past few years is evidence that the industry may, in fact, be entering a period of sustained growth. The establishment of a solid, theoretical technological base and the presence of many large and traditionally conservative corporations has, in effect, legitimized the industry. However, it is wise to view the optimistic forecasts for industry growth with the knowledge that historical market performance has fallen far short of prior expectations.

The experience of the Japanese robot industry is a good predictor of how the United States industry might evolve. We can expect the United States robot industry to become less and less concentrated. This is due to the relatively low barriers to entry in the industry, and the relative importance of applications experience versus robotic experience. Firms from a broad range of technological tracks can enter the industry and leverage their existing applications experience, product lines, and marketing systems. The Japanese experience is evidence of the advantage that nichers have relative to firms trying to address the market at large. Thus, we can expect the share of the eventual market leader to be no more than ten to fifteen percent, and the four firm concentration ratio to be on the order of thirty to forty percent. The low barriers to entry and the strong international competition will tend to keep profitability at "normal" levels. As sales volumes increase, large vertically integrated manufacturers will be able to implement cost reducing technologies and will, thus, be at an advantage to those firms that continue to license systems. However, the component nature of robot systems, and the efficient international markets for them, will minimize the economic advantages of vertical integration. There will continue to be room for systems integrators.

Japan poses both opportunities and threats to United States manufacturers. It will continue to be a source of technology for firms seeking to license proven robot systems, and a potential market for United States manufacturers. However, it is clear that both individual Japanese firms and M.I.T.I. have hopes of dominating world markets for robot technology, in the manner of Japanese electronics and automobile manufacturers. They are addressing their acknowledged weakness in computer control hardware and software through internal research and joint industry-government research. M.I.T.I. recently launched a seven year, $30 million program to develop highly intelligent, general purpose robot systems by founding a joint research association comprised of ten major robot, computer, and machine tool manufacturers [34]. The United States robot industry soon may no longer be able to congratulate itself for its technological superiority over Japanese manufacturers.

A number of factors have prevented Japanese robot companies from entering the United States market directly. Their unfamiliarity with United States markets and lack of distribution channels have created the incentive to seek ties with United States companies. In addition, friction between the United States and Japan over the balance of trade has discouraged the large scale invasion of Japanese robot companies. However, forecasts of the United States market penetration of Japanese manufacturers in 1985 range from twenty percent to nearly fifty percent [425]. It will be especially interesting to see what happens when the licensing agreements signed in the last few years begin to expire. If United States manufacturers do not renew the agreements, choosing instead to market internally developed systems, it is very likely that the Japanese firms will enter the market directly. Furthermore, the "factory of the future" concept creates an opportunity for Japanese firms. Many United States firms are already looking to Japan to learn modern manufacturing management techniques such as "kanban," and quality circles, in addition to learning from their applications experience with robot systems. The opportunity will exist for Japanese firms to export this total package of manufacturing and management techniques on a systems consulting basis. Who better than a Japanese company to look to for assistance in designing and setting up a new manufacturing plant?

We can expect to see more interfirm research and development and industry funded academic research as a response to the concerted Japanese development effort. In addition to the previously mentioned research programs at Renssalaer and Carnegie-Mellon, industry sponsored robotics research is proceeding at a number of other United States universitites. The proposed establishment of a semiconductor research institute funded by a number of leading United States computer and semiconductor manufacturers is evidence of the awareness of the need for interfirm cooperation on basic research. The FTC is expected to make it easier for firms to share the costs of basic research in response to the planned industrial research programs of Japanese and European governments. In addition to bolstering the industry's international competitiveness, such interfirm technology sharing will help smaller, less well financed robot manufacturers compete with the larger firms (IBM, General Electric) in the industry. The net result should be a more competitive, less concentrated albeit less profitable industry.

The continual learning by end users and their increased sophistication with respect to robot technology is bound to have an important effect on the industry. The effectiveness of the "turnkey" system strategy relies on end users' unfamiliarity with technology and resulting need for engineering support. However, as the technology diffuses through academia and industry, end users will be more able and willing to engineer their own systems. In most machinery and plant engineering departments of large companies, engineers design factory machinery and utility systems by specifying the best and most appropriate components. Outside consultants are used on jobs that are too complex for in-house staff, or if internal resources are stretched too thin. The result is that many components, such as industrial controls, motors, conveyors, etc., have become commodities ordered from catalogs. There is no reason to believe that such a design process will not characterize the robot industry, once enough users become sufficiently sophisticated to specify their own systems. The component nature of robot technology makes it especially prone to such a future. If robot components do become somewhat "commodity-like," the implication for strategy is that cost leadership will become relatively more important, and turnkey support will become less important.

However, we can expect robot manufacturers to resist the trend towards commodity components by "bundling" their own components, and by making it difficult to integrate other manufacturers' components. Just as office automation and E.D.P. vendors have found it difficult to agree on networking and interfacing standards, robot manufacturers will undoubtedly resist component interchangeability. The future of such interfacing standards, and of component interchangeability will depend on the relative market power of customers versus producers. By diversifying the customer base away from the concentrated heavy manufacturing industries and towards the less concentrated light manufacturing and electronics industries, robot producers will be able to maintain a modicum of leverage over customers. However, the large number of participants and the presumably unconcentrated nature of the robot industry will act to lessen their bargaining power with users. I believe that market demand will create opportunities for component suppliers, and will, thus, force the hand of robot manufacturers to adopt interfacing standards. The timing of these important changes is still unclear, but we might expect end users to have enough experience with robot systems to be able to specify components in five to ten years.

Much of the current academic research and development is aimed at developing robotic systems for environments other than the factory floor. Unmanned submarines with robotic manipulators install and maintain transoceanic cables. It is expected that robotic technology will be applied in industries as diverse as mining, agriculture, and space exploration. Indeed, the unmanned Viking Explorer is one of the most sophisticated examples of robot technology. It is doubtful that companies that now produce manufacturing oriented robots will be able to address these other applications directly. Similar to the manner in which spray painting equipment manufacturers have acquired robot technology through licensing and joint ventures, firms manufacturing mining equipment or agricultural equipment will likely pursue such interfirm technology transfer. The demand for robotic component technologies in these other industries will be added incentive for robot manufacturers to modularize their components and make them interchangeable.

Nearly all of the trends in the industry point to decreasing concentration and increasing competition. Such healthy competition will undoubtedly cause marginal firms to fail, and will prevent any single firm from earning significant "monopoly" profits. Furthermore, many analysts predict a "shake out" of the smaller, marginal firms in the near future, expecially if the economic recovery is not as strong as is hoped. The implications of this vigorous competition for users of robot systems are very positive.

5. Summary and Conclusions

The purpose of this thesis is to describe and analyze the evolution of the robotics industry. Of particular interest are firms' strategic responses to evolutionary forces. These forces include technological and marketing changes in the immediate industry and in adjacent industries, as well as exogenous forces such as the oil shock and trade protectionism. The robotics industry was chosen for study because of the impact it is expected to have on the United States and world economies. In addition, the technological diversity inherent in robotics and the high degree of international activity in the industry make it particularly interesting.

The first two Sections discussed robot technology and applications. It was shown that robots are electromechanical systems comprised of several distinct component technologies. These components include the robot arm, drive system, end effector, controller and sensors. Of these, the controller and sensors are the most technologically dynamic, and have had and will continue to have the biggest impact on the industry. The development of versatile control and sensor processing software is felt to be the key to making robot systems more useful and generally applicable. This diversity of component technologies has created opportunities for a broad range of existing firms. Furthermore, the relative technological maturity of the components affects firms' ability to successfully enter the robot industry based on experience with a given component technology. A key element of the robot manufacturers technological strategy was shown to be the degree to which a robot is designed as a sophisticated, general purpose machine, or as a simpler specialized system.

The technological sophistication and cost of the robot systm is naturally a function of its application. Robots are not used as stand alone devices, rather, they are integrated with other processing, machining or materials handling equipment to form a manufacturing system. The applications for robots can be characterized as "pick and place," assembly, and processing. Of these, "pick and place" were the simplest and earliest applications, while assembly is the newest and most complex application. Processing robots account for fifty to sixty percent of current sales, "pick and place" for thirty to forty percent and assembly for five to ten percent [20]. However, assembly is expected to become more and more important, and should account for thirty to forty percent of robot sales in 1990 [17].

The balance of the thesis discussed the evolution of the United States robot industry. Although it is generally thought to be in the emerging or early growth stage of the classical industry life cycle model, close examination shows that the industry has passed through four empirically distinct stages in its twenty-five year history. The first of these was the "embryonic" stage (c. 1959-1965), in which the initial innovation occurred and the first robot manufacturers were incorporated. The early manufacturers were firms experienced in machine design and industrial controls. Unimation soon established itself as the technological and market leader, although total industry sales in this period were on the order of only $5 million to $10 million per year. Important characteristics that emerged during the embryonic stage were the importance of applications engineering and the role of the customer in identifying applications and specifying requirements for robot hardware.

The next stage (c. 1965-1970) can be though of as a period of "diffusion" of robot technology. In the mid 1960's, robotics research labs were established at a number of United States universities, and work began on applying computer control to robotic manipulators. The diffusion of robot technology from industry to academia is contrary to the pattern of most modern technological innovations, in which academic research usually precedes commercialization. In 1967, robots were introduced to Japan by A.M.F. and Unimation. Unimation soon licensed a Japanese company to manufacture and market its Unimate robots in Japan. For a number of reasons, the Japanese were more receptive to the technology than were United States or European firms, and the next decade saw the establishment of strong Japanese robot market and industry. However, market performance in the United States continued to be slow, forcing two of the initial entrants out of the industry.

The 1970's was a decade of many new technological developments. Most noteworthy was the introduction of the first computer controlled robot by Cincinnati Milacron in 1973. Milacron, a leading machine tool manufacturer, soon became the number two robot producer. Other companies soon followed suit, and by the end of the decade, computer and microprocessor control became a standard feature in robot systems. The other important technological development was the application of robots in processing applications such as welding and spray painting. DeVillbiss, a manufacturer of spray painting equipment, entered the market by licensing robots from a Norwegian manufacturer, and integrating them with their own processing hardware. Their entry established a pattern for firms seeking to enter the industry by leveraging their existing technology and marketing channels. It also pointed out the development of an efficient international market for robot components. This, in effect, lowered the technological barriers to entry for United States firms. The robot market was further segmented by a number of firms that began to offer simple, non servo robots appropriate for pick and place applications. The net effect of these technological and marketing innovations was the stimulation and growth of demand. By 1980, the annual sales of United States based robot manufacturers had grown to $90 million.

The last few years have seen an "explosion" in the industry in terms of demand and entry of new firms. Demand continues to grow in excess of forty (40%) percent per year, and is expected to result in industry sales of over $500 million by 1985, and over $1 billion by 1990 [18]. In response to the opportunities this growth will provide, many new firms have entered the robot market. These firms range from huge multinationals such as IBM, General Electric and General Motors to small venture capitalized start ups. Their motivations and strategies for entry are very diverse, although some form of interfirm relationship has characterized most of the entries. Examples of such relationships include licensing of proven robot technology in the mode of DeVillbiss, a joint venture between a Japanese robot manufacturer and United States supplier of vision systems, and the acquisition of Unimation by Westinghouse. The spate of interfirm relationships again reflects the integrative nature of robot technology and the efficient worldwide market for robot components. The entry of so many firms having different technological tracks and different motivations has given rise to a wide spectrum of competitive strategies.

Having documented and analyzed the technology, end users, and firms involved in the industry, we can now answer the three general questions posed in the introduction to this thesis. These questions are:

1. Why did robot technology give rise to a distinct industry?

2. What factors have caused it to evolve the way it has?

3. What might we expect the future of the industry to be?

The concept of flexible, general purpose industrial robots was certainly not first conceived in the late 1950's. In fact, the word "robot" was introduced to the English language in 1922, by a Czech playwright, who used it to describe artificial beings manufactured to replace human workers. In addition, we have shown that the commercialization of the first robot systems in the late 1950's was not the result of a significant technological breakthrough, but rather, the result of identifying an appropriate application. Unimation seized the opportunity to become the first manufacturer of general purpose, reprogrammable robot systems. This opportunity presented itself because of the nature of industrial automation at that time. Most automation systems were designed to address very specific applications. Furthermore, such systems were often designed and manufactured in-house, by internal engineering states. The high development and engineering costs and the impracticality of designing general purpose devices for specific needs prevented user firms from developing robot systems for internal needs. The small engineering firms that also designed automated production equipment tended to have a very specific industry or applications focus, usually designing systems conceived and specified by customers. Therefore, the existing suppliers of automated equipment, be they in-house or independent, were so focused on specific applications and customers, that they had little incentive to conceive of or market a general purpose device for a broadly defined market. An individual company with limited applications had little incentive to develop a flexible, easily programmable device, when it could instead design a customized simpler, hard automation system. In order for such development to be practical, the producer must be able to market it to many firms, in effect spreading the development cost across many firms. The robot industry can thus be thought of as an engineering staff which no single user could justify, but the user industries as a whole can justify. It is the general purpose nature of robot technology, and the lack of existing firms with the incentive or resources to develop such technology, that gave rise to a robot producing industry.

A number of important factors have influenced the evolution of the industry. Although the creation of the robot industry was due to the general purpose nature of the technology, it soon became clear that applications expertise would be an important factor. This is because the robot is not a stand along device that is simply inserted into an existing production process. It must be integrated with other machinery, and very often must be equipped with customized end effectors and fixturing equipment. In fact, it appears that applications expertise -

knowing how to use robot technology effectively in a given application - is relatively more complex than knowing how to manufacture a robot. This basic fact explains the entry into the industry of robot users and firms having expertise with specific applications (e.g., welding, spray painting). Even though robot arms are essentially general purpose devices, the high applications engineering content of a robot system has created niches and paths of entry for many firms.

Another important factor is the broad range of technologies that are embodied in a complete robot system. THis diversity of component technologies has created opportunities for machinery designers, computer manufacturers, control system manufacturers, machine tool manufacturers, etc. to enter the industry. Furthermore, the integrative nature of the technology has spawned a great number of interfirm relationships. Firms have taken advantage of such strategies to realize technological as well as marketing synergies. The ready availability of partners for such interfirm relationships has, in effect, lowered the barriers to entry to the robot industry. Now a firm with a particular application or technological expertise can become a robot producer by licensing proven robot technology, or entering into a joint venture with an existing robot manufacturer. The range of component technologies and the integrative systems nature of robotics explains the high number and diversity of firms now involved in the industry.

In particular, the use of computer technology to control robot systems has "changed the game" for robot producers, and has opened up many new applications for robot technology. Just as microprocessors and computer technology have changed the watch industry, the cash register industry, and the typewriter industry, they have inexorably change the nature of the robot industry. The application of computer technology has stimulated demand by making robots more useful, and has changed the technological "pre-requisites" for participation in the industry.

International trade has played an important role in the evolution of the industry. Frustrated by United States industry's lukewarm reception to their technology, Unimation looked to overseas markets in an attempt to broaden its customer base. In addition to providing Unimation with licensing revenues and a larger customer base, this early worldwide diffusion had important long-term effects. Proven robot technology is now being "re-imported" by United States firms seeking to enter the market. An efficient worldwide market for robot components has stimulated the entry of many new firms and has generally increased the level of competition in the industry. However, in a broader sense, this early international diffusion has also helped United States robot manufacturers. The intense international competition in robot using industries (e.g., automobiles, electronics manufacturing) was in part, stimulated by the early Japanese adoption of industrial robots. United States and European firms are now rushing to "robotize" their factories in an effort to regain their international competitiveness. The early diffusion of robot technology has had the effect of stimulating demand here at home, albeit with a bit of a time lag.

We can expect the United States robot industry to develop in a manner similar to that of the Japanese robot industry. Because of the relatively low barriers to entry, and because of the ability of nichers to effectively address specific applications, the industry will become less and less concentrated. International competition, most notably from Japan, will also tend to make the United States industry more competitive and less concentrated. Finally, the increasing sophistication of end users will eventually result in their desire to specify robots on a modular, component basis. In addition, the application of robot technology for applications other than manufacturing will give rise to a demand for robotic components, and the incentive to form interfirm relationships in the mode of DeVillbiss, et. al.

Naturally, the net effect of these competitive forces will be to drive marginal firms out of the industry, and to keep industry profits down to "normal returns." In fact, 1982 saw intense price competition as a result of the many new entrants, and lower than expected demand due to the recession.

Because of the intense applications engineering nature of the industry, and because of end users' relative unsophistication, we can expect firms to continue to pursue the "turnkey" systems strategy. However, as shipments increase, we can expect large, integrated robot manufacturers to be able to realize economics of scale in production, and to pursue strategies of cost leadership. The increased sophistication of end users and their ability to specify their own systems will be an added pressure for manufacturers to shift from systems strategies to high volume production of components.

Though it is difficult to generalize based on the history of a single industry, there are a few significant trends underlying the robotics industry that could well have applicability to other industries.

The initial robot innovation was of more of an engineering nature than of an exploratory, scientific nature. In fact, the theoretical work in robotics followed its initial commercialization. However, the academic research of the 1960's had a great effect on the commercially available technology in the 1970's, and really "changed the game" for the initial players in the industry. Unimation was "leapfrogged" technologically by Cincinnati Milacron, and was forced to acquire computer expertise. Firms that are "first-in" to an industry must be very cognizant of staying technologically competitive, especially if their initial introduction preceeded academic and theoretical research.

The spectrum of opportunities arising from the diversity of component technologies has attracted firms with a range of technological and marketing capabilities. Integrative technologies create so many opportunities for entry that it is unlikely that any single firm can achieve significant market power. The implication for public policy is that it can promote interfirm activity and technology sharing without the fear of promoting monopolistic competition. The international diffusion of robot technology occurred very early in the industry's history. Given the increasing equivalent levels of technological sophistication in the industrialized countries, such a strategy of early international diffusion can enable a firm to leverage international competitive forces in user industries. This appears to be especially true of productivity and energy related technologies.

Further research in comparing the histories of different industries would enable us to further generalize about strategic responses to evolutionary forces. It would be especially interesting to compare and contrast the robotics experience with other technologically diverse, engineering oriented industries.

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FIGURES AND CHARTS