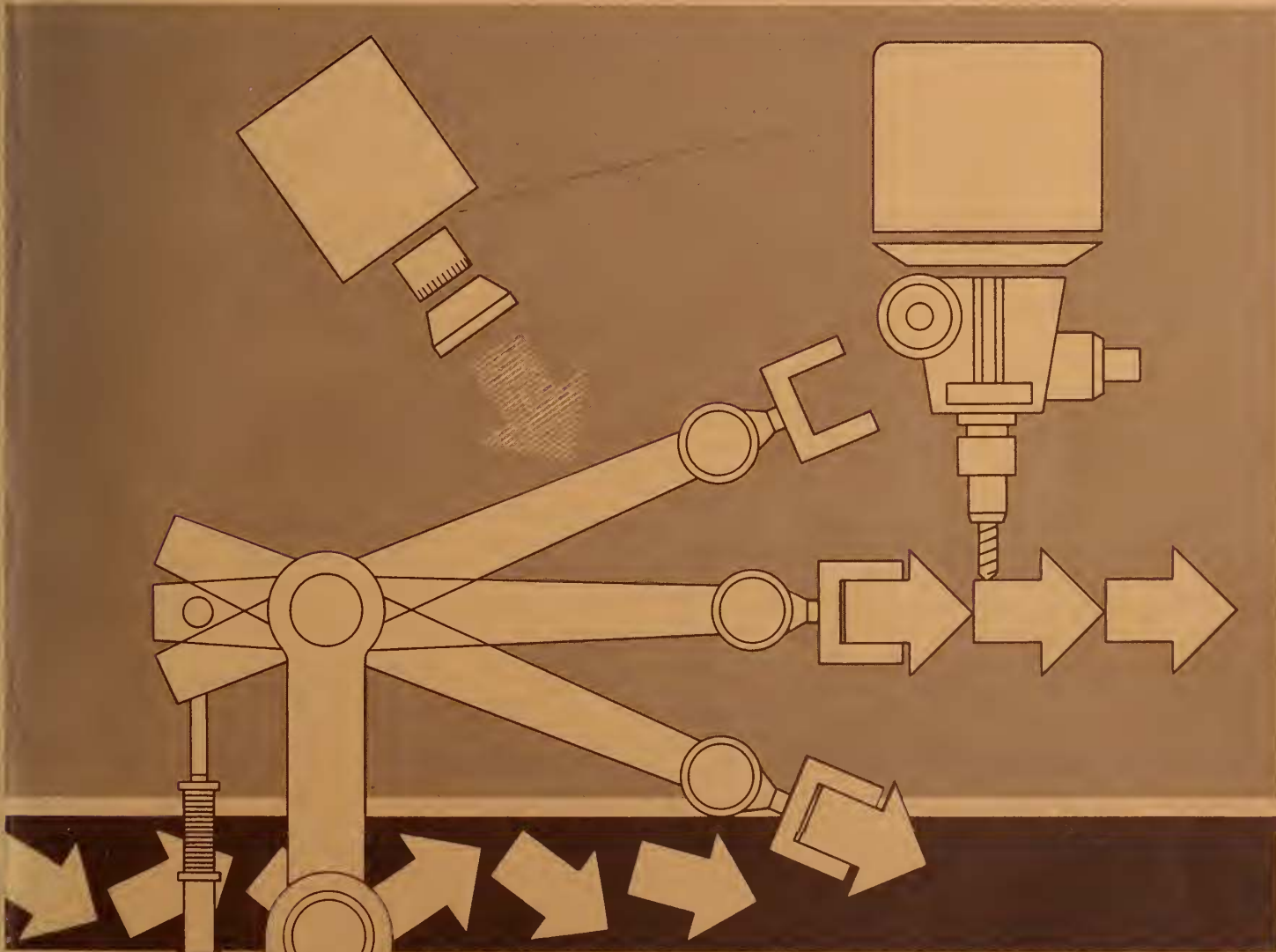# An Overview of Artificial Intelligence and Robotics
Volume II - Robotics

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AN OVERVIEW OF ARTIFICIAL INTELLIGENCE AND ROBOTICS VOLUME II - Robotics

William B. Gevarter

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Manufacturing Engineering
Industrial Systems Division
Metrology Building, Room A127
Washington, DC 20234

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

This is the second volume of a two volume NBS/NASA report on an <u>Overview</u> <u>of Artificial Intelligence and Robotics</u>. This report is intended to be read by the interested technically-oriented layman, such as engineering managers, government funding officers, and others who desire an overall perspective of the field but are unable to obtain it from the highly technical and unintegrated literature in the field, or from the more flamboyant but non-technical feature articles in the popular press.

The report incorporates a summary of the basic concepts utilized in each of the many technical areas, a review of the state-of-the art, an indication of the organizations involved together with their funding sources and principal activities, research requirements, and a 5-10 year forecast of the emerging technology.

As robotics is a very rapidly changing field - with new companies, products and researchers entering the field each month - a report like this can only be regarded as an imperfect snapshot in time, and would benefit from periodic up-dating. Thus, quantitative information shown in this report may perhaps best be regarded as indicative rather than authoritative. Despite such shortcomings, this report should be helpful in providing a base, for organizations and individuals in and out of the government, for planning future robotic research and develop-ment, applications and utilizations.

Acknowledgments

I wish to thank the many people and organizations who have contributed to this report, both in providing information, and in reviewing the report and suggesting corrections, modifications and additions. However, the responsibility for any remaining errors or inaccuracies must remain with the author.

It is not the intent of the National Bureau of Standards to recommend or endorse any of the manufacturers or organizations named in this report, but simply to attempt to provide an overview of the robotics field. However, in a diverse and rapadly changing field such as robotics, important activities and products may not have been mentioned. Lack of such mention does not in any way imply that they are not also worthwhile. The author would appreciate having any such omissions or oversights called to his attention so that they can be considered for future reports.

AN OVERVIEW OF ROBOTICS

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I. <u>Introduction</u>

Robots in use today are primarily machines with manipulators that can be easily programmed to do a variety of manual tasks automatically. The robot con-sists of one or more manipulators (arms), end effectors (hands), a controller, power supply, and - increasingly - sensors to provide information about the en-vironment and feedback of performance in task accomplishment. The motivation for most current robotic development is industrial: to increase productivity, reduce costs, overcome skilled labor shortages, provide flexibility in batch operations, improve product quality and to free humans from boring, repetitive tasks or operations in hostile environments.

Table 1 gives the Japanese standard classifications for industrial robots (IR's) by input information and teaching method, and relates this to the U.S. classification by control method - non-servo or servo.

As indicated in Table 2, the Japanese are the world's largest user of robots. Counting all classifications of robots the Japanese had approximately 77,000 robots in use at the end of 1980 (Yonemoto, 1981, p. 1). Table 3 presents the Japanese robotic use by industry, based on robot costs. It seems that the electrical machinery and automobile industries are the largest users of robots. Less than 1% of IR's are utilized outside of manufacturing. Table 4 presents the 1979 Japanese usage by production process. It is apparent that over 60% of the usage is for moving or positioning a workpiece. This is reflected (see Table 5) in the predominance in 1980 robot production of the fixed sequence type of robots.

Of the many reasons for installing industrial robots, the most prominent ones are to increase productivity and reduce costs. A commonly used measure for determining the ecomonics of installing robots is the payback period. This is

Table 1
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.

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 names 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 servo-mechanisms 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.

Table 2

IRs in Operation
(As of the End of 1979)

Japan	14,000 Units	(69%)	
United States	3,255	(16%)	
West Germany	850		
Sweden	600		Total
Italy	500		20,268 (100%)
Poland	360	Western Europe	
France	200	3,013	
Britain	185	(15%)	
Norway	170		
U.S.S.R.	25		
Belgium	13		

(Note) Manual Manipulators and Fixed Sequence
        Robots are not included.

Source: Sadamoto, 1981, p. 52.

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Table 3

Principle Users of Industrial Robots in Japan

	Share in 1980 (Based on Value)
Electric Machinery Industry	36%
Automobile Industry	30%
Plastic Moulding Products Industry	10%
Metal Working Industry	5%
Metal Working Machinery Industry	4%
Steelmaking, Textile, Chemical, Shipbuilding and Misc.	15%

Source: Yonemoto, 1981, p. 2

Table 4

JAPANESE ROBOT USAGE BY PRODUCTION PROCESS

Process	% of Total
Loading & Unloading	40
Transfer & Sorting	21
Palletizing	9
Welding	6
Work Maintenance	4
Assembly	3
Spraying	2
Other (Including Pouring, Screwing, Riveting, etc.)	15
Total	100

Source: Research Div., Long-Term Credit Bank of Japan, 1981, p. 28.

Table 5

JAPANESE PRODUCTION OF ROBOTS BY TYPE IN 1980

Type	Unit	Value ($ Million)
Manual Manipulators	1,940 (10%)	13 (4%)
Fixed Sequence Control Robots	13,440 (67%)	104 (31%)
Variable Sequence Control Robots	1,340 (7%)	43 (12%)
Playback Robots	2,030 (10%)	71 (21%)
NC Robots	990 (5%)	97 (29%)
Intelligent Robots	130 (1%)	10 (3%)
		Sub-Total (100%)
Other Robot-Related Devices		10
Total	19,870 (100%)	348

Source: Ogawa, 1981, p. 132.

usually given (see for example, Simons, 1980, p. 32) as the cost of the robot

and accessories (including fixtures, etc.) divided by the annual savings:

$$p = \frac{I}{L-E}$$

where   p = payback period in years

I = total investment

L = total annual savings in labor

E = total annual robot upkeep cost.

Typically, automation investments have required that the payback period be three

years or less, with actual payback periods reaching as low as one year when

multiple shifts are utilized.

II. Primitive Functions Accomplished by a Robot

Industrial robots are primarily designed for manipulation purposes. The primitive actions imposed at the hand by the manipulator are:

1. Moving

   - from point to point

   - following a desired trajectory

   - following a contoured surface

2. Changing Orientation

3. Rotation

Non-servo robots can provide a sequence of point to point (PTP) motions. For each motion, the manipulator members move full tilt until the limits of travel are reached. Thus they are often referred to as "bang-bang", "pick and place" or "limited sequence" robots. "Programming is done by setting up the desired sequence of moves and by adjusting the end stops for each axis" (Tanner, 1979, p. 7). The use of mechanical stops and limit switches yields good positional accuracy, which is typically repeatable to better than $\pm$ 0.5 mm (Simons, 1980, p. 20).

Servo-controlled robots can be designed to provide a sequence of PTP motions, with controlled intermediate velocities. They can also be used to follow a programmed trajectory or by using sensors to follow a contoured surface.

If we consider end effectors, the robot can also be made to grasp, push and pull, twist, use tools, perform insertions and assembly, and do other manipulations done by humans.

If sensors and appropriate computations are added, the robot can perceive, inspect, recognize, test and do many of the other perceptual functions now done by humans.

All applications require that the robot interact with the environment in the execution of its programmed task. Thus the robot is often designed to

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switch machines on and off and to accept information from machines as to their status. The robot may also have provisions for accepting signals from a moving assembly line, so it can track it. Similarly, the robot may have interface provisions for tactile, visual or other sensory inputs for feedback control.

III. Manipulator Arm Configurations

To accomplish these primitive actions, four basic configurations of manipulator arm designs have evolved:

(a) Rectangular   (Figure 1a)

(b) Cylindrical   (Figure 1b)

(c) Spherical   (Figure 1c)

(d) Anthropomorphic, articulated or
        jointed arm   (Figure 1d)

These arms utilize both rotary ("revolute") and linear ("prismatic") joints, as appropriate, to accomplish their function. Six degrees of freedom (6 DOF requires 6 joints) are necessary to locate the end effector (hand) at any point and orientation in the work volume. More DOF's are sometimes used to prevent interference of the arm with the work piece or other obstacles. As few as 2 or 3 DOF may suffice for a simple "pick and place" robot.

As indicated in Figure 1, only three DOF's are required to position the end effector. However for applications requiring a high degree of wrist flexibility, as many as three of the arms DOF's are located in the wrist. These DOF's are usually referred to (using aeronautical terms) as pitch, yaw and roll.

The basic four manipulator arm configurations can be combined in various ways to produce a bewildering set of manipulator combinations. These combinations can be further extended by employing angled arms and offsets. Often built-in mechanical linkages are added to do such things as constrain the motion of nominally articulated arms to cylindrical coordinates for ease of control.

In addition, the arms may be designed to be mounted on their sides, hung from the ceiling, or mounted on rails for mobility, to further multiply the range of installed configurations.

Figure 1

Basic Manipulator Geometries

Cylindrical Coordinates
b.

Articulated or Jointed Spherical
(Revolute Coordinates)
d.
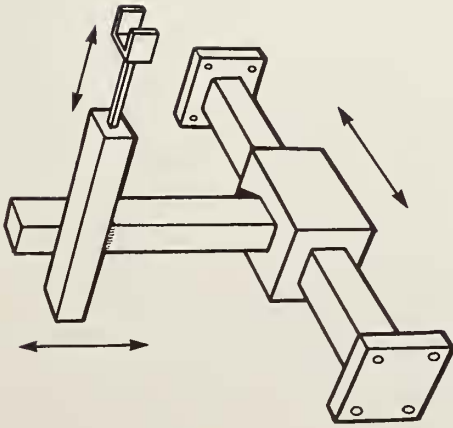
Rectangular
(Cartesian Coordinates)
a.
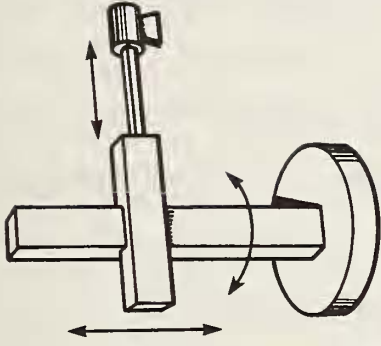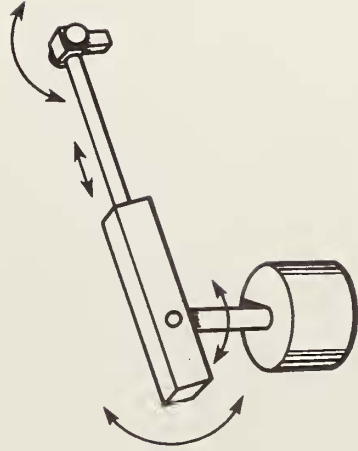
Spherical
(Polar Coordinates)
c.

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IV. Actuators

There are three major ways today of powering the actuators that move the manipulator joints: pneumatic, hydraulic and electrical. Pneumatic is simple and inexpensive but "squooshy" and is best used for "pick and place" robots whose trajectory motions are controlled by mechanical stops. Hydraulic actuation (currently the most popular system) is capable of high-power for a given size, but suffers from leakage problems as well as requiring pumps, storage tanks and other accompanying paraphenalia. Electrical-mechanical actuation is clean but doesn't offer good power to weight ratios. Stepper motors are inexpensive but sometimes lose pulses and therefore accuracy. D.C. torque motors are very reliable, offer good controllability, but can be expensive. Because the overall cost advantage of hydraulic systems diminishes with size, electrical drives are to be preferred for the small robot.

Actuators are the most problem-prone area of robotics. Thus considerable research is needed in this area to further improve reliability (robots have an approximately 98% up-time these days) and to reduce costs and weight.

V. Mobility

At present, most robots in industrial applications are fixed inplace or ride along rails, guideways or conveyors. Simple robot carts for transporting materials are now being used in industrial and commerical applications. Robot vehicles using wheels and treads have been researched by NASA for planetary exploration purposes.

Crawling robots, using their manipulator arms to grasp handholds, are being explored by NASA for use in constructing large structures in space. Walking machines are still in the experimental stage, with research going on at Ohio State University, Carnegie Mellon University (CMU), Tokyo Institute of Technology, and in the Eastern Block countries. Engelberger (1980, p. 63) states that "Practical robot devices with legs could have advantages in such applications as arctic transport, mining, agriculture, forestry, fire-fighting, explosive ordance disposal, unmanned ocean-floor surveys, and planetary exploration".

VI. End-Effectors

The hand or gripper, sometimes called the "end-effector", (attached to the robot wrist) can be a mechanical, vacuum or magnetic device for part (or object) handling or for tool manipulation. At present, most of the these interchangable devices are grippers which are simple open-and-close devices. The variety of tools and grippers that can be adapted for robot use is virtually unlimited (see for example, Engelberger, 1980, pp. 41-58). The end-effectors are usually unique to the robot application and thus customarily provided by the user, though several manufacturers offer a broad selection of devices for grasping parts that might be adaptable to the particular task being performed. Nevertheless, though hundreds of different special-purpose end-effectors now exist, the end-effector remains one of the major limiting factors in universal robot manipulation due to lack of dexterity and programmability of the hands. Extensive research and development is now underway to produce grippers that can handle a wide variety of part configurations.

VII. Control

Control of robot arms ranges from highly repeatable open loop devices to servo-controllers that utilize external sensors in the control of robot actions.

Open loop devices may be as simple as a step sequencer and positionable mechanical stops for a pick and place robot, to more complex devices using stepper motors to reproduce a desired motion.

Servo-devices can use internal sensors, such as joint position sensors, or external information sensors such as force, proximity devices, and even vision (operating under computer control).

Servos operating only on internal sensors require very careful positioning of the work-piece (which can require expensive fixturing or feeding devices).

Servos utilizing data from sensing the external environment, require more complex processing of the signal, but yield much more flexible systems.

The controller, in addition to controlling the manipulator motion, often also serves as an interface to the outside world - coordinating the robots motions with machines and assembly lines and turning on and off machines that it is operating.

A. Pick and Place Robots

The simplest controllers are non-servo (open loop) devices that rely on sequencers and mechanical stops to control the manipulator end-point positions along each of the axes. These "limited sequence" robots are also referred to as "pick and place," "bang-bang," or "fixed stop" robots. These robots have no provision for trajectory control between the end points.

B. Programmable Robots

Programmable robots are servo controlled robots of two basic types: "point-to-point" and "continuous path."

Point-to-point robots are directed by a programmable controller that memorizes a sequence of arm and end-effector positions. Hundreds of points may be memorized. The robot moves in a series of steps from one memorized point (set of point positions) to another under servo control, using internal joint sensors for feedback. Because of the servos, trajectory control between the memorized points is possible and relatively smooth motions can be achieved.

Continuous path robots do not depend on a series of intermediate points to generate a trajectory, but duplicate during the playback process the continuous motions recorded during the teaching process. Thus, these robots are used for painting, arc welding and other processes requiring smooth continuous motions.

C. Computerized Robots

Computer-controlled robots are capable of being programmed "off-line" using a high level programming language and do not have to rely on being physically taught.

D. Sensory Robots

These are computerized robots that interface to the outside world thru external sensing such as sight or touch. These "intelligent robots" are capable of adapting to a variety of conditions by changing their actions based on relating the sensed information to their goals or preprogrammed decision points.

E. Robots as Part of a Flexible Manufacturing System

A flexible manufacturing system (FMS) is a programmable batch-processing arrangement that contains programmable machine tools and transfer devices all under central computer control. When robots are used in such a system, the robot controller may itself be just the bottom layer of a hierarchical control system for the FMS (c.f. Topperwein, et al., 1980, pp. 96-105, or Albus, 1981A, pp. 261-280).

VIII. Sensor-Controlled Robots

Sensor-controlled robots are the first step on the path to truly intelligent robots - robots that can determine their own actions based on their perception and planning abilities.

The simplest versions of sensor-controlled robots utilize contact switching for stopping the arms and for opening and closing grippers. More sophisticated robots are now beginning to use touch, force and torque sensing. Forces and torques can be derived from stress measurements or from internal signals (e.g. derived from back EMF). Tactile information may be derived from deflection-induced resistance variations of a special sensing surface, or by various other ingenious approaches.

Work in France and at MIT on "artificial skins" with embedded arrays of touch sensors, opens the possibility of a robot eventually being able to determine position, orientation and identity of parts by touch alone. This may be particularly important for difficult assembly operations (Kinnucan, 1981). Proximity and range sensing are also now being considered.

Vision, the most complex of all the sensory modalities, is now beginning to find its way into robotic control.

IX. Robot Vision

In the industrial manufacturing arena, to circumvent the problem of requiring that the workpiece be in a prescribed position and orientation (pose) for the robot to operate upon it, sensory systems are now beginning to be employed. Vision provides perhaps the most flexible approach to avoid all the fixturing that would be required to achieve a fixed pose.

Figure 2 lists the desired functions of a machine vision system to achieve fully flexible sensor-controlled manipulation. Figure 3 indicates potential applications for such a system.

A. Methods for determination of pose:

1. Range can be determined in four principle ways:

- Stereo

- Triangulation

- Active ranging (e.g. time of flight of light or sound)

- Using optical focusing.

2. Orientation can be determined by:

- Observing the relationship of three (or more) known object points that are not all colinear in the viewing field, provided that the relative ranges connecting these points are known.

- Deriving surface normals using the intrinsic image concept (Barrow and Tennenbaum, 1981).

- Deducing it based upon the response of lighting on the object, utilizing known characteristics of the object. (This is simplified if structured lighting such as sheets of light are employed).

- Interferometry measuring the phase differences of an oscillating signal received at multiple points.

Figure 2

Desired Functions of Machine Vision for Sensor-Controlled
Manipulation in Industrial Manufacturing

° Recognition of workpieces/assemblies and/or
  recognition of the stable state where necessary.

° Determination of the position and orientation of
  workpieces/assemblies relative to a prescribed set
  of coordinate axes.

° Extraction and location of salient features of a
  workpiece/assembly to establish a spatial reference
  for visual servoing.

° In-process inspection -- verification that a process
  has been or is being satisfactorily completed.

Source: Rosen, 1978.

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Figure 3
Block Diagram of Potential Vision Applications in Robotics
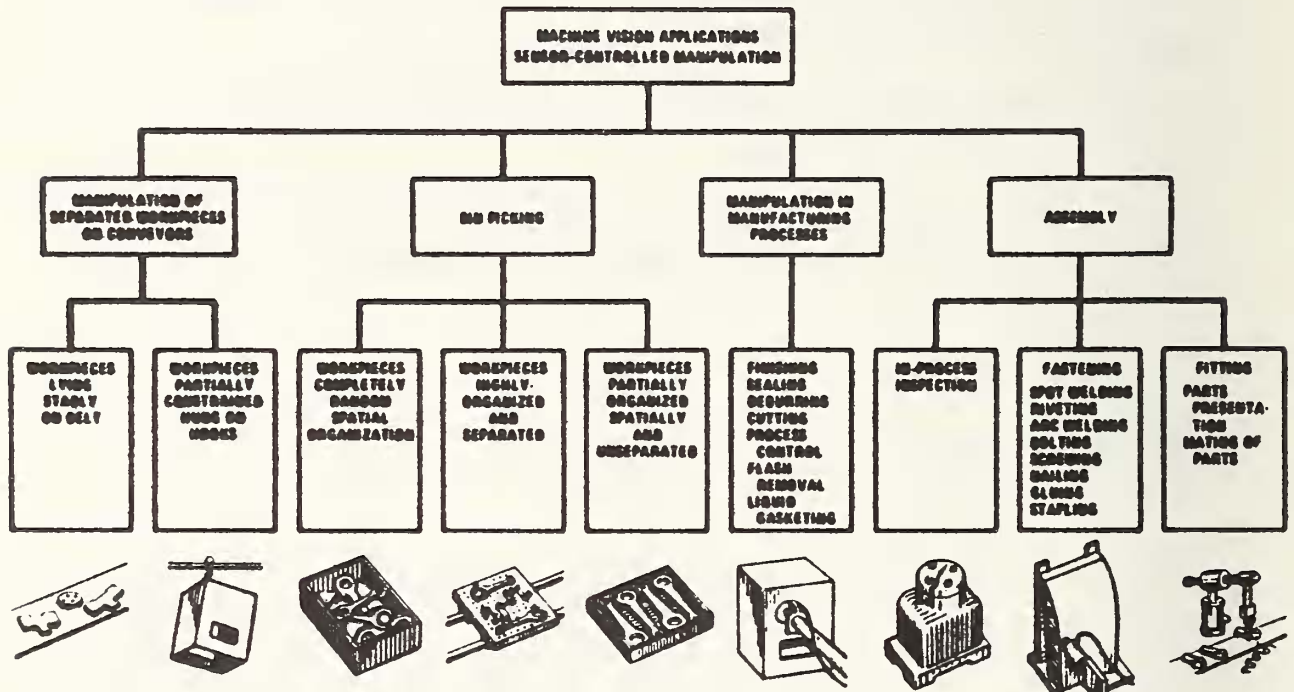
B. Feature Extraction

Though it is possible to operate directly on an analog output of a vidicon imager (by such approaches as optical correlation, or template matching), it is now fashionable to use solid state imaging arrays, such as CCD or CID devices, which directly provide points (pixels) in the image.

These pixels are then digitized by intensity levels (usually 2 to 16) so as to be put in a convenient form for operation upon by a computer. From this data, edges and regions are determined. Edges are considered to occur when there is an intensity gradient exceeding a selected threshold. These gradients are derived from intensity differences between adjacent pixels (often using an averaging scheme to reduce noise effects). Regions are grown by annexing ("clustering") adjacent pixels that are close to the same intensity level. Various schemes (heuristics) exist to connect lines having gaps, smooth irregularities, and remove discontinuities in regions (all resulting from noise in the image). The result (which can be considered as a form of data compression) is a reduced image that consists of edges and regions. Further data compression might be achieved by representing edges by sets of straight or curved lines (the ends and curvature of which are all that need to be known).

C. Object Recognition

Having determined edges and regions, it is possible using the methods of Section A to determine position and orientation. However, often it is necessary to determine which object is being observed from a collection of possible objects. This may be accomplished by

1. Template Matching: Using a stored image in the computer.

2. Use of Edge and Region Statistics: This may be curvature of edges, area moments of inertia, ratio of square of perimeter to area, number and/or location of holes or notches, etc.

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3. <u>Fourier Transform</u>: Determining the coefficients of the spatial Fourier transform and comparing them to the coefficients of known objects.

D. <u>Future Techniques</u>

In the future we may see:

- Greater use of direct range measurements - e.g. scanning laser radar, or LED's and photo diodes using phase or intensity measurements.

- Parallel processing to obtain feature extraction in real-time.

- Improved methods for determining edges and regions.

- Use of optical markings for recognition, for optical code reading or for determination of pose.

- Use of intrinsic image analysis - to determine surface orientation, depth, relationship of foreground to background, and texture.

- Scene analysis for less-structured situations.

X. Programming a Robot

    There are four primary methods for programming a robot:

* Physical-setup, in which the operator sets up programs by physically fixing stops, setting switches, arraying wires, etc. This is characteristic of the simpler robots.

* Lead-through, in which the operator leads the robot through the desired positions and locations by means of a remote teach box. (These points are recorded and used to generate the robot trajectory during operation.)

* Walk-through, where the robot arm is physically manipulated through the desired motions (which are recorded and then played back by the robot-control during operation).

* Writing a software program, which is then executed when desired.

    The emphasis in programming research today is on software programming of computer-controlled robots. Work on sensor-controlled manipulation is extending the scope for programmability. Interacting with the robot by means of software, provides more flexibility then the other programming methods, and allows for conditional actions or flexible adaptations. Various high level robot programming languages such as VAL (Unimation) and AML (IBM) are now beginning to become available to aid in the software generation.

    Simons (1980, p. 107) notes that software programs can be divided into two types: "In explicit programming, the user requires explicit instructions for every action the robot must take. In world modelling, the robot is more autonomous and can make decisions according to its knowledge. World-modelling systems, largely in the research stage, tend to require a considerable amount of computer power but are able to carry out complex tasks. The most important world-modelling languages are AL, AUTOPASS, and LANA..."

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XI. Kinematics and Dynamics

A. Coordinate Transformations

If the arm is programmed by walking-thru, then it is simply necessary to record the simultaneous joint positions during the walk-thru. If the arm is led-thru, then in more sophisticated systems, that can operate in tool point, world, or other coordinate systems, it is necessary to do the needed coordinate transformations for each joint in order to obtain the desired end-effector orientation and position. This is particularly true when the arm is being programmed by writing software.

When the arm is controlled via feedback from a vision or other sensor, it is necessary to do coordinate transformations to convert the camera or hand coordinates to base or computer coordinates. For vision (or other sensor) control, the sensor interpretation and coordinate transformations need to be done in real time. As the mathematics for exact transformations requires time-consuming calculations, approximate simplifications have been developed to speed the calculations. In some systems, individual microprocessors are used to process the kinematics at each joint.

Note that arms are often designed so that the wrist motions are mechanically constrained to cylindrical or rectilinear coordinates to simplify control and reduce coordinate transformation requirements.

B. Trajectory Selection

For moving the end effector from one position (or point) to another, various schemes are possible for choosing the motions for moving the joints. Approaches for articulated arms include:

- Variations from preprogrammed paths.
- The "dominant axis" approach: some joints may be allowed to adapt while others follow fixed movements.

- All joint motions move proportionately relative to the slowest joint, so that all joint motions terminate at the same time.

Considerations of this sort become particularly important for off-line or real-time programming of computer-controlled robots.

C. Dynamics

At present, all robot arms are made relatively stiff so that structural flexibility is minimized (to promote repeatability). However, this requires stiff and usually heavy arms with high power actuators, lowered carrying capacity, and reduced speed. Research is now underway on the control of structurally flexible arms to help overcome these limitations, and in active control to control flexure for achieving on-line precision under load as during assembly or drilling operations. The 15 meter long Romote Manipulator System (RMS) for the Space Shuttle is probably the most extreme case of a structurally flexible manipulator thus far.

XII. Research Requirements

A. Different Views

In considering research requirements it is very helpful to differentiate between near-term needs and far-term needs. Figure 4 indicates the near-term needs for improvement in IR's, as perceived by Japanese users. Note the emphasis is on robot flexibility and versatility of movement, speed, and ease of programming.

In observing how private enterprise is responding to the IR user desires, Umentani (1981, p. 81) indicates that the robot manufacturers most important targets for development include:

  · reduced production costs

  · smaller installation space requirements

  · greater flexibility

  · larger carrying capacities

  · modular robots components to enable a building block approach to
    diversification of functions

  · visual and tactile feedback and recognition systems

Table 6 lists the main research subjects being pursued by Japanese Robot Manufacturers. These may be regarded as relatively near-term. Note the correspondence with user desires in their emphasis on speed, flexibility and programming versatility.

As we move towards the longer term, we encounter robot research such as is being pursued in Japanese Universities and Japanese Government

Figure 4

1980 JIRA User Survey of Desired Improvements in Industrial Robots

Greater Degrees of Freedom

More Compact Size

Increased Speed

Larger Assortment of Attachments

Easier Reprogramming

Greater Reliability

Increased Working Volume

Increased Payload Capability

Increased Accuracy

Tactile Sensing

Vision

Pattern Recognition

Increased Memory

Mobility

Coordinated Control of Multiple Robots and Machines

Others

50   100   Cases
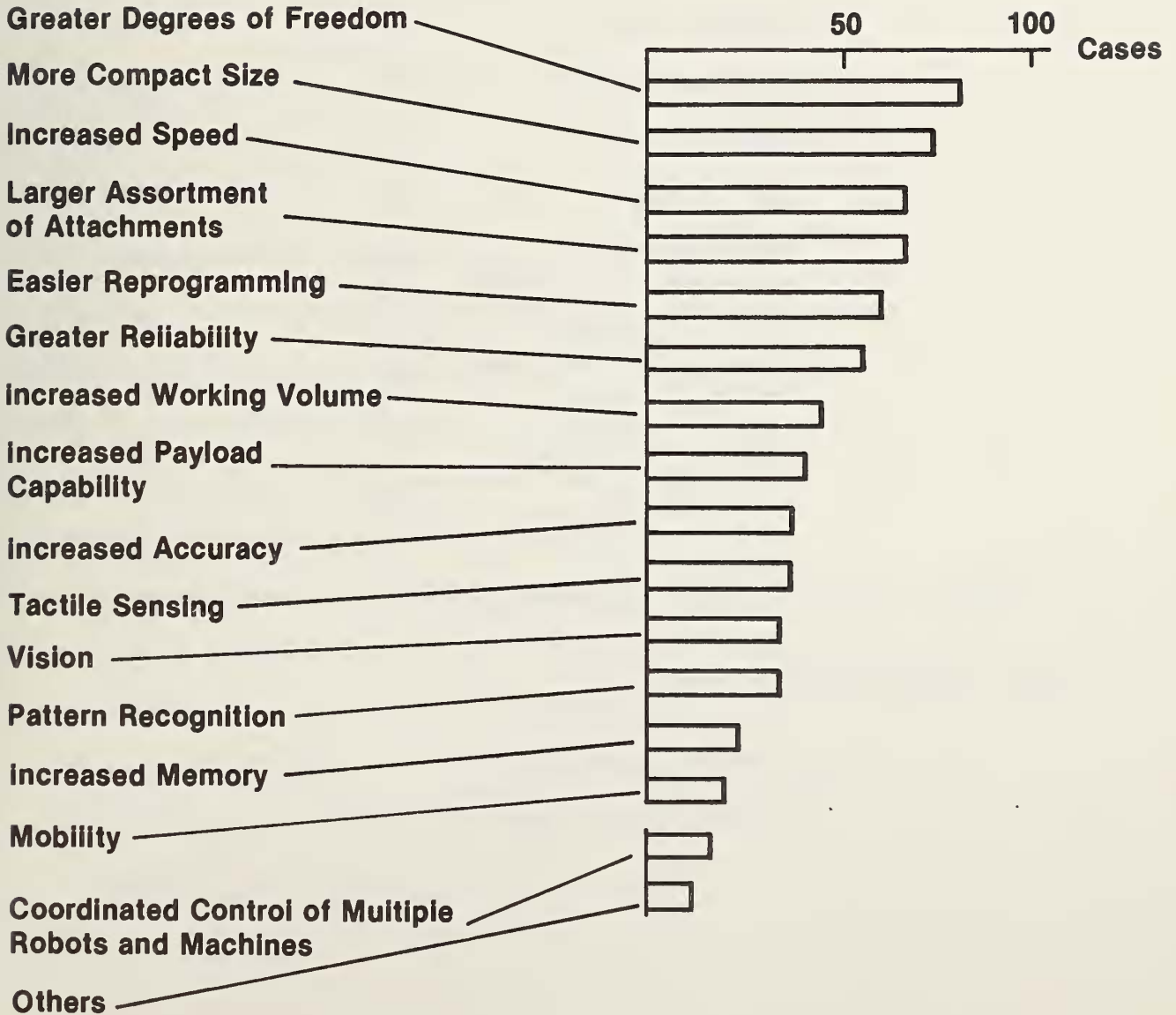
Source: Umentani, 1981, p. 84.

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Table 6

Main Research Subjects In IRs
1980 JIRA Survey of Japanese Robot Manufacturers

Order of Importance	Subject	No. of Research Subjects	% of Total
1	Increased Speed	49	13.1
2	More Compact Size	36	9.7
3	Computer Control	32	8.6
4	Lighter Weight	30	8.0
5	Interchangeability by Module	25	6.7
6	Object Recognition	19	5.0
7	Increased Payload	17	4.6
8	Improved Actuators	14	3.8
9	Self Diagnosis	14	3.8
10	Adaptive Control	14	3.8

Source: Umentani, 1981, p. 98.

Research Institutes. Here a 1980 JIRA research survey indicates (see

Umentani, 1981, pp. 95-96) that their primary research topics (in decreasing

order by number of research projects) are:

- control
- locomotion
- vision
- tactile sensing
- manipulators
- end effectors
- programming methods and tools

Figure 5 lists the desirable goals for future robots (from a U.S.

vantage point) as seen by Engelberger (1980). He states (p. 125) that

of the missing robotic attributes, the two most cruical ones are vision

and tactile sensing. As indicated in Figure 6, this view is shared by the

particpants in the NBS/RIA Robotics Research Workshop.

Kelley and Huston (1980), Birk and Kelley (1981), and Albus (1981B)

have also attempted to come up with research requirements for future

robots, though they did not attempt to prioritize them. Their requirements

are summarized in Figure 7. In the following discussion we will combine these

research needs into categories for ease of presentation.

Figure 5

Desirable Goals for Future Robots

1. Rudimentary sense of vision to provide

    a) recognition data
    b) orientation data

2. Tactile sensing to provide

    a) recognition data
    b) orientation data
    c) physical interaction data

3. Computer interpretation of the visual and tactile data

4. Multiple appendage hand-to-hand coordination

5. Computer directed appendage trajectories

6. Mobility

7. Minimized spatial intrusion

8. Energy conserving musculature

9. General purpose hands

10. Man-robot voice communication

11. Total self diagnostic fault tracing

12. Inherent safety (Asimov's Laws of Robotics)

13. All the capabilities above available for a price which allows
    purchase and operation within the traditionally accepted rules
    for economic justification of any new equipment

Source: Engelberger, 1980, p. 118.

Figure 6

Recommended Distribution of U.S. Robotics Research Funds/Effort

	%
Binary Vision	14
Gray Scale Vision	12
Off-line Programming	12
Control Systems	11
Touch, Force, Torque Sensing	11
End Effectors	10
Integration Into CAM Systems	8
Mechanical Systems	7
Simulation and Modeling	6
Safety	4
Mobility/Line Tracking	4
Others	1
	────
	100%

Source: NBS/RIA Robotics Research Workshop, 1979, p. 49.

Figure 7

Basic Research Needs in Robotics (not prioritized)

Kelley and Huston (1980)   Birk and Kelley (1981)

Manipulator Kinematics   1. Intelligence
Control
Locomotion   Knowledge Representation
Sensing   Auto. Prob. Solving,
Artificial Intelligence   Decision Making, Planning
Higher-Order Languages
Smaller Actuators   2. Control

                                            Flexible Structures Control
                                            Modeling
                                            Real-time Sensory Control
                                            Fault Tolerance, Monitoring
                                                and Repair

Albus (1981B)   3. Actuation

Accuracy   4. Manipulation and Hands
Speed and Dexterity
Sensing   Performance Evaluation
Control   Kinematic Planning for
Knowledge Representation   Assembly
Programming (Higher Order Languages)   Speed
Standardized Interfaces (Modularity)
Mobility   5. Dexterity

                                    6. Locomotion

                                    7. Sensing

                                            Vision
                                            Tactile
                                            Real-time Computation

                                    8. Programming

                                    9. Adapation and Learning

B. Synthesis of Needed Research

1. Manipulator and Actuator Design:

To achieve the higher speeds, flexibility, accuracy, efficiency and dexterity that is desired in future robots, additional research in manipulator arms are needed. For large manipulators and precision work, joint and arm structural flexibilities can be a problem. Therefore stiff, but lightweight arms are desirable to minimize this problem and to aid in increasing speed. However as variable compliance in different directions is often desirable to provide the "give" needed for inserting parts and other assembly operations, unique design approaches may be required.

At present, actuators are one of the more problem-prone areas of robots. In addition, actuator efficiencies are in the order of one tenth that of human musculature. Smaller, more reliable and efficient actuators and drive mechanisms, with high load to weight ratios, are needed for the high speed, lighter weight robots of the future.

For greater dexterity and less intrusion into the work-zone, it is also necessary to understand the mutual interdependence of end effector and manipulator kinematics. Also research on micro-manipulators is needed for applications to micro-electronics and biology.

A unified theory is needed on how to design an arm for smooth universal movements, satisfaction of functional requirements, and to provide the required load capacities throughout its motion spectrum. A standardized approach to performance measurement and evaluation is required to enable comparison of robots not only in such factors as working volume, load capacity and reliability, but also in aspects such as speed, smoothness and accuracy throughout their operating range.

To help determine manipulator accuracy (now a limiting factor in off-line programming of open-loop manipulator operations), a universal stochastic model of mechanical errors of manipulators needs to be devised.

2. End Effectors

Umetani (1981, p. 110) states that "the most difficult barrier in industrial robot design... is the design of dexterity in hands and fingers." Thus, much work is needed to devise designs for general purpose hands (and the means to control them), such that the whole arm need not move to provide the desired dexterity. Because general purpose hands are not yet available, multiple end effectors may be required for a single application. This in turn requires some type of quick change wrist design.

3. Control

Kelley and Huston (1980) indicate that further research is needed on the basic robot problem: given the desired external or absolute displacement, velocity and acceleration of the hand, determine the optimal physical and internal motion parameters. (Birk and Kelley, 1981) state that procedures have been recently developed for efficiently obtaining and solving governing dynamic equations for robotic systems with flexible links and joints. However, optimizing the arm motion still presents problems of convergence and uniqueness (Kelley and Huston, 1980).

Though the repeatibility of arm positioning via open-loop (no external sensory feedback) robot control has been good, accuracy for initially positioning the arm via open-loop control has been poor. In addition, no efficient means of robot cali-bration has yet been determined. Thus it is important that more work be done on improving open-loop control accuracy. Accuracy degradation due to flexure can be a particularly troublesome problem when trying to perform precision operations under load, such as drilling without the aid of jigs.

An important area of control not yet solved is control of structurally flexible manipulators. This problem, important to high speed manipulation with manipulators having high load to weight ratios, may require real-time simultaneous management of a large number of command and control variables. An associated problem with such manipulators may be the large changes in moments of inertia as the manipulator is extended and a load applied. Another problem associated with high speed manipulation, requiring additional research, is the generation of time-optimal trajectories.

An area for which little is known about ideal solutions, is the control of redundant-axis manipulators used to provide additional manuever capability.

Design of control systems for fault tolerance will become particularly important as robots become more autonomous.

Finally, lack of suitable strategies for control of multi-fingered hands is still one of the principle factors retarding design of dexterous hands.

4. Sensory-Controlled Manipulation

One of the most desirable features for improving robot flexibility is sensory capability. Vision, the most popular U.S. robot research area, appears to be the most desirable sense for present and future IR's. Next in importance is touch.

To take full advantage of sophisticated sensory data, real-time control using sensors is needed. Hierarchical control may be the appropriate means to handle such data, though control logic systems such as pattern reference feedback logic may be appropriate in certain contexts.

In addition to vision and tactile sensing, dynamic control using force feedback is an important area of research. Also of increasing importance as robots become more autonomous, is proximity sensing as used before final contact and to avoid obstacles. Other sensors will increasingly have roles in inspection and in determining the type of material being observed. Research is needed in the use of models in sensory processing and interpretation.

It is also necessary to explore the tradeoff between the use of sensors and imposing more structure on the robot environment. As sensory control is perfected, the tradeoff will undoubtedly shift towards the direction of using sensors.

5. Vision

Vision becomes more important as the environment becomes less structured. Therefore vision is needed more for fire-fighting, household servants, robot explorers, etc., than for IR's. Vision can also reduce manipulator accuracy requirements, by making real-time adjustments practical.

At the current state of the art, additional research in recognition and geometric representation is needed. As greater capability is desired, three dimensional vision combined with world models and spatial reasoning will become important. Current

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3-D research in vision systems center on the use of range-finding, structured light, and binocular vision systems. Further-out, research is required in the analysis of image sequences (optical flow: shape from motion), intrinsic image analysis (determining shape from a single image by disambiguating the response to light), and improved methods to recognize objects in clutter. The bin-picking problem is a classic one in this latter area.

One of the most important research areas in vision is approaches to improve the speed of visual processing. This includes research in computational elements structured for visual processing, which includes parallel-processing CPU's, and special chips for edge-finding, Fourier analysis, etc.

6. Tactile and Force Sensing

What is needed is better use of contact sensing data. This includes better resolution in touch and force sensing. An important result could be the ability to recognize parts and to determine their relative position and orientation through such methods.

7. Programming a Robot

Programming by teaching is not practical for small lot production, particularly when sensory interaction is involved. Thus, improved techniques are needed for generating robot control data. These could include high-level programming languages, software debugging tools, world models, and the ability to directly utilize CAD data bases and sensory inputs. Robot simulation tools can aid in off-line programming. Also needed are better geometric modeling systems. As robot usage advances, it would be desirable to produce aids for writing programs to orchestrate multiple arms and multiple sensors, and for systems with distributed control.

8. Intelligence

Plantier and Bodmer et al. (1981, p. 63) assert, "Artificial Intelligence is the technological area which needs most to be developed and mastered to accelerate robot evolution." Birk and Kelley (1981) indicate that an intelligent robot is

one capable of:

- receiving communication
- understanding its environment by the use of models
- formulating plans
- executing plans
- monitoring its operation

Thus research in all these areas is important.

Communication: Use of a natural language interface, or computer graphics or even voice commands would all be helpful in simplifying communication with a robot. In addition, intelligent aids for robot users to help plan and develop robot usage are also needed.

Knowledge Representation: A key ingredient in advanced robotics is knowledge representation. However, the tradeoff between control algorithm complexity and representation complexity needs to be explored. Sophisticated internal models of the environment are needed to generate expectations, to interpret sensory data, and for use in automatic generation of robot control data (such as for real-time decision-making).

Representations are also needed to enable qualitative reasoning about physics and space for use in planning and problem solving.

Parallel processing will be needed to make real-time modeling a reality.

Planning: Automatic problem-solving or planning is one of the keys to future intelligent robots. Planning is even needed for acquiring information from sensors. Needed is research on ways to use large amounts of domain-specific knowledge to guide planning and responses to recognized situations.

One of the difficult, but important areas of research needed is in developing plans that deal with time.

For certain tasks, the software for handling contingences is becoming excessive. Thus means for automatic monitoring and correction are needed. In addition, plan-monitoring and repair is also in need of research. It would also be useful to be able to store successful plans in categories so that they can be reused. In general, it is desirable that the system be capable of adaptation and learning.

Automatic assembly in non-highly structured environments is a key research area. Development of kinematic strategies for assembly is needed. Assembly could be aided by model-based generation of programs that use local sensory information in assembly tasks. Research is also needed for planning and orchestrating the actions of cooperating robot systems for assembly and other purposes.

Intelligent controls can be thought of as coupling control theoretic approaches with advanced AI methodolgies. To advance this area, better understanding of modular hierarchical structures is needed as well as how to generate hierarchical plans associated with such structures.

To make intelligent robots really useful, it is necessary to develop methods that will enable them to function in real-time (not having to pause for computation) with realistic computers.

9. Robot Mobility .

For industrial robots tending machines, furnaces, etc., the robots are often in use only a fraction of the time, the remainder being in a wait mode. To make better use of the robots, machines are frequently arranged so that one robot can tend several machines. Sometimes this involves moving the robot (motion along tracks being the usual means). Locomotion is needed to further extend the working range and for use in hazardous environments and in remote locations. In many cases, a truly mobile robot would be preferred that can be used where needed. Mobile robots

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would be particularly advantageous in environments less structured than that found in factories, such as in the construction of ships, buildings and roads, in mining, and in undersea or space use.

New mechanical mechanisms, other than wheels, are needed for mobility over uneven terrain. However, mobility systems tend to amplify compliance and vibration problems (which can be minimized by careful design and the use of sensor-driven control). Active suspensions are needed for uneven terrains, climbing, etc. For legged vehicles, the key problems are stability, control and optimal motion synthesis. In walking machines very little is known about the stability of various gaits. Advances are needed in the hierarchical control of multi-body systems. Efficient algorithms need to be developed for solving the governing dynamic equations.

If the mobile robot is to be supervisory-controlled, then optimal partitioning of the task between the operator and machine becomes an important research area.

10. Modularity

Further work is needed not only to develop modular manipulators, but also to enable integrated modular systems that can consist of a variety of robots, tools, sensors and computers all connected together. To do this, standardized interfaces are needed. It will be necessary to partition the control problem into modular components and to develop interface standards for communication between these components. An important goal is to be able to write an off-line program for one robot and be able to use it with a differently designed robot.

The 1980 NBS/Air Force ICAM Workshop on Robot Interfaces (1981) considered the following items for standardization.

 · simple sensor interface between simple peripheral devices and a robot control system.

- Wrist interface between the robot wrist and the end effector.

- Complex sensor interface that covers vision, complex touch
  and other such sensors.

- Common robot control interface, providing robot independent
  trajectory descriptions.

- Robot Programming Languages

- Integration of robots into robot systems for automated manufacturing.

It was concluded that both the simple sensor and wrist interfaces were ready for standardization, but that it was too early in the development of the other areas to begin a standards effort at that time.

XIII. Commercially Available Robots and Components

Engelberger (1980, p. 117) indicates that many of the attributes required to make industrial robots practical in an industrial environment are available today. These (see Figure 8) include good positioning repeatability, reliability, flexibility, easy programmability and adequate load capacity, all at a affordable price.

The rapid growth of industrial robots (roughly 35% per year) and the entry of new manufacturers and new products makes its inappropriate to try to list or even summarize all the robots currently available. However, the following are good sources of information to keep current with available robot products:

* Robotics Age, a bimonthly magazine popularizing robots, P.O. Box 725, La Canada, CA 91011.

* Robotics Industry Directory published yearly by Robotics Age, P.O. Box 725, La Canda, CA 91011. This directory lists complete information on over one hundred different models of currently available robots, robot components and peripherals. It also provides information on robot distributors, robot research institutes and consultants in the robot field. Robot Systems and Products, providing a monthly new products update, is also available from Robotics Age.

* Specifications and Applications of Industrial Robots in Japan published by Japan Industrial Robot Association (JIRA), 3-5-8, Shiba Koen, Minato-ku, Tokyo, Japan. A 1982 edition is currently available. JIRA is a good source for all information on Japanese robots.

* Robotics Today, a quarterly magazine on industrial robotics published by the Society of Manufacturing Engineers in cooperation with the Robot Institute of America, One SME Drive, P.O. Box 930, Dearborn, MI 48128.

Figure 8

Robot Attributes Now Commercially Available

1. Work space command with six infinitely controllable
   articulations between the robot base and its hand
   extremity

2. Teach and playback facilities - realizing fast,
   instinctive programming

3. Local and library memories of any practical size desired

4. Random program selection possible by external stimuli

5. Positioning accuracy repeatable to within 0.3 mm

6. Weight handling capability up to 150 kilos

7. Point-to-point control and continuous path control,
   possibly intermixed in one robot

8. Synchronization with moving workpieces

9. Interface allowing compatibility with a computer

10. Palletizing and depalletizing capability

11. High reliability -- with not less than 400 hours MTBF

12. All the capabilities available for a price which allows
    purchase and operation within the traditionally accepted
    rules for economic justification of any new equipment

Source: Engelberger, 1980, p. 117.

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· The Industrial Robot, a quarterly magazine with a European orientation toward

industrial robots, published by IFS Ltd., 35-39 High St., Bedford MK42 7BT,

England.

An excellent recent guide to industrial robots for perspective users -

Sanderson, R. J. et al., Industrial Robots: A Summary and Forecast for Manu-

facturing Managers, 1982 - can be purchased from TECH TRAN Corp., 134 N. Washington

St., Naperville, IL 60540.

In addition, various robotic newsletters (such as "Robot News International,"

also available from IFS Ltd., "Industrial Robots International," available from

Technical Insights, Inc., P.O. Box 1304, Ft. Lee, N.J. 07024; and the "Robotics

Newsletter," available from Bache, 100 Gold St., New York, NY 10038) offering

information on new robot products and investments have recently begun to appear.

Datamation, Byte, Business Week, Time and other technical and popular magazines

have also recently begun to have feature articles on robotics.

At the end of 1981, there were some 50 U.S. based firms marketing or pre-

paring to market robots (Conigliaro, 1981), the leaders being:

· Unimation Inc. (projected to have 32% of the estimate $215 million

(3075 units) U.S. market in 1982) and Cincinnati Milacron (projected to

have 25% of the U.S. market in 1982).

Several of the large U.S. auto, electrical and computer firms have been building

robots for internal use and are now entering or considering entering the com-

merical robot market.

Japan at the end of 1981 had over 130 different manufacturers producing robots, many for their own internal use. Table 7 presents the robot production by major Japanese manufacturers for the years 1980 and 1981. Of the estimates by JIRA of 19,400 robots, valued at 77 billion yen, produced in Japan in 1980, only 3% were exported.

In 1979, approximately 2400 robots were sold in Europe. European manufacturers having a major share of this market include:

    ASEA - Sweden

    Olivetti - Italy

The Eastern Block Communist countries have been moving in the direction of robots to make up for their serious labor shortages. Business Week (Aug. 17, 1981) reported that the Soviets plan to manufacture 40,000 robots by 1985 to counter not only the shortage of skilled labor, but also absenteeism associated with drinking.

Table 7

Number of Robots Produced by Major Japanese Robot Manufacturers

Note: The figures in brackets indicate approximate value.

Company	1980 Achievement	1981 Target	Major Product Function
Kawasaki Heavy Industries	450 ($22 M)	650 ($31 M)	Spot welding Arc-welding
Yaskawa Electric	360 ($16 M)	630 ($29 M)	Arc-welding
Hitachi	150	480 ($22 M)	Spot welding Arc-welding
Mitsubishi Heavy Industries	120	240	Spot welding Print-spraying
Kobe Steel	120 ($7 M)	200 ($13 M)	Arc-welding Paint-spraying
Star Seiki	-	($13 M)	Plastic mould picking
Shinmeiwa Industry	360 ($4 M)	480 ($9 M)	Arc-welding
Fuji Electric	130	200 ($9 M)	Inspection
Fujitsu-Fanuc	480 ($4 M)	600 ($7 M)	Machine processing Assembling
Sankyo Seiki	-	300 ($4 M)	Assembly
Nitto Seiko	-	120 ($3 M)	Assembly

Source: August 1981 Survey (Survey Japan, 1981, pp. 210-211).

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XIV. Commercially Available Vision Systems for Robots

Present commercially available vision systems for use with robots are
basically devices that generate and analyze 2D images. These systems recognize
objects by their silhouettes. Principle current manufacturers of sophisticated
computer vision systems are:

> Machine Intelligence Corporation (M.I.C.)
> Sunnyvale, CA

> Automatix Inc.
> Burlington, MA

> Octek Inc.
> Burlington, MA

M.I.C. Vision Module

This Vision Module is based upon prototype software and hardware developed
at SRI under NSF and industrial affiliate support (see Gleason and Agin, 1979).

The Vision Module consists of a solid-state TV camera, a preprocessor inter-
face and a LSI-11 microcomputer. The vision software, stored in the LSI-11 memory,
includes the entire library of vision subroutines previously developed at SRI,
several application programs (such as training-by-showing and execution of part
recognition), as well as newly developed capabilities. The capability to develop
application programs by calling the vision-library subroutines makes the Vision
Module a general-purpose vision system. The Vision Module is intended for a
variety of industrial vision applications such as inprocess inspection, sensor-
controlled manipulation, and visual servoing.

The Vision Module can recognize parts on the basis of their size and shape
regardless of their position or orientation. The part (lying in one of its
stable states previously used to train the module) is recognized on the basis of
a set of shape descriptions, including area, perimeter, number of holes,
length of major and minor bounding ellipse axes, first and second moments of
area, etc., and various algebraic combinations of these.

The Vision Module operates by appropriately thresholding the image in the
preprocessor to achieve binary silhouettes of the objects in the scene. A frame
buffer stores the binary image (consisting of zeros and ones) to achieve timing

independence between the camera and the controlling microcomputer. Each line is sequentially scanned and "run-length" encoded (i.e., edge points recorded where the pixels change from zero to one or vice versa). Each run-length segment on a line is matched against segments of the previous line to determine their overlapping relations hips. Using these relation ships, the program traces the appearance and disappearance of blobs (regions) as the image is processed from top to bottom. Only one line at a time of image data needs to be stored in the computer.

At the heart of the vision processing are connectivity analysis routines which segment the image into contiguous regions (called "blobs") even in the presence of noise. During the connectivity analysis, sequences of perimeter points are extracted. Using this blob boundary information, other desired parameters such as area, area moments, shape, position and orientation of the blob can be computed.

The system is trained by showing the object to the TV camera resulting in all potentially useful shape descriptions being automatically calculated and stored. Then the same object is moved and photographed several times and the mean and variance of these descriptors calculated and stored. This resulting set of means and variances, can be used as a "prototype" for that object or class of objects. New objects can then be recognized in either of two ways. One, by using a normalized nearest-neighbor method, where the best fit of the features of the new object to the set of prototypes is selected. Two, using a binary decision tree (which can be built by the Vision Module software upon command) recognition is done by measuring one feature at a time, and at each stage subdividing the recognition problem into two smaller problems until a single choice remains. The time to read in, process and implement recognition is in the order of one second.

Complete vision systems cost from $30-40 thousand dollars. M.I.C. also markets the VS-110 Machine Vision System version for real time inspection tasks.

M.I.C. which is currently rapidly expanding, is placing increased emphasis on turnkey systems, and improved man-machine interfaces. The problems of resolution speed and cost are also being vigorously attacked.

The Automatix Autovision System

The Autovision System (Rheinhold and Vanderbrug, 1980) also uses the SRI algorithms as its main base for vision processing and in many ways is similar to the MIC system. However, the Autovision System's preprocessor (Scheinman, 1981) has a pixel memory capable of storing several images at once, or several bits of grey level information, or any combination. The versatility of the system comes from the system's powerful AI-32 control processor, which with its 32 bit internal design and megabyte memory address space, can operate in parallel with the preprocessor and has the ability to interface with multiple preprocessors and various other input and output devices. The control processor operates under an Automatix developed operating system. Most of the system software is factory programmed in PASCAL, except where speed or compactness is so critical that assembly language is used.

The primary interface for the user is via the Automatix application language, RAIL, which is designed for the non-computer oriented user. This powerful and flexible robot programming language makes it possible to sequence the operations of the Autovision system so that the desired task can be performed.

Octek Vision System

Octek has several vision systems based on a circuit board developed in 1980. It can handle two high resolution solid state TV cameras with 320 x 480 pixel arrays. The system has an on-board microprocessor that can manipulate images at four frames per second. The system can handle a 16 gray level scale.

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There are four memory planes so that similarities and differences between images can be determined. The system relies on a Data General or DEC computer for computation. The basic circuit board costs about $4500, with the cost of a complete vision system ranging from $16,000 to $40,000.

KEYSIGHT AND CONSIGHT

At General Motors, several different computer vision systems are now operational (Rossol, 1981). KEYSIGHT is an example of a system for inspection tasks in automobile manufacturing. It uses a low-resolution solid state camera to inspect for the presence or absence of valve spring cap keys on automobile engines. Ingeniously applying fairly standard computer vision algorithms for edge finding, etc., the system locates the center of the valve spring assembly and then, based on the keys being brighter than the holes they fit over, determines if the keys are present.

More interesting is CONSIGHT, an example of a robot vision system that uses structured light to detect the silhouette of passing objects. Using a robot arm, CONSIGHT transfers a moving stream of non-touching, randomly oriented parts from a moving conveyor belt to a predetermined location.

Structured light provides a means to deal with situations that require both high spatial resolution and fast response. It allows part geometry to be sensed directly, as opposed to being inferred through grey level picture processing.

CONSIGHT is logically partioned into independent vision, robot and monitor subsystems. When the vision subsystem has seen the entire object, it sends to the monitor the object's position and belt position reference value. The robot subsystem then executes a previously "taught" robot program to transfer the part from the belt to a fixed position.

A single narrow and intense line from two parallel, separated sources
is projected across the belt surface perpendicular to the belt's direction of
motion. A linear array camera builds a conventional two dimensional silhouette
imate of passing parts by collecting a sequence of these image strips. For each
object detected, a small number of numerical descriptions is automatically
extracted for part classification and position determination.

CONSIGHT is now commercially available, having been licenced to Unimation,
Cincinnati Milacron, M.I.C. and Automatix.

XV. Current Robot Research

In Japan

        Robot related research in Japan can be placed into three categories - research
done by universities and research institutions, by industry, and by special govern-
ment sponsored task forces. A 1980 JIRA survey found that a total of 88 research
projects were then underway at universities and public and private research
institutions. However unlike the U.S., there were no large-scale research efforts
at the universities or technology colleges.

        Areas of emphasis in research projects at Japanese universities and research
institutions are (Hasegawa, 1981, pp. 162-163):

        · increasing robot speed

        · coordination of multiple arms

        · dexterous robot hands with tactile recognition capability for
          automatic assembly

        · sensory development for intelligent robots

        · robot locomotion

        · robot control and application software development

In the United States

        Robot research in the U.S. is primarily aimed in the direction of making
robots more intelligent and versatile, with vision research being given a high
priority. Albus (1981B, p. 7) states, "Much remains to be done in sensor technology
to improve the performance, reliability and cost effectiveness of all types of
sensory transducers. Even more remains to be done in improving the speed
and sophistication of sensory processing algorithms and special purpose hard-
ware for recognizing features and analyzing patterns in space and time."

        Robotic research efforts at U.S. universities (roughly reflecting FY-82
funding) are indicated in Table 8. Note that the research is centered on greater

Table 8A

Robotics Research

Institution: Stanford University

Principal
Researchers: Thomas O. Binford, Bernard Roth,
Robert Cannon, Larry Leifer
(23 Grad Students, 4 PostDocs)

Research Funding: Approx. $1,400 K/year from NSF, ARPA
and NASA

Manipulation

- Control of flexible manipulators

- Control of multiple manipulators

- Design of three-fingered hand

Perception

- Robot Vision

- Stereo Mapping

- Special purpose VLSI for vision

- Segmentation

- Force sensing and control

Programming and Intelligence

- AL (arm language) one of the most advanced robot programming
  languages available today.

- ACRONYM system for geometric modeling and reasoning for model-
  based vision and for programming robots.

- Work on CAD, resulting in a simulator for mechanical systems
  and robot arms, and for off-line programming.

Mobility

- A continuing program of navigation and perception.

Table 8B-1

Institution: Artificial Intelligence Lab., M.I.T.

Research Funding: $1.75M DARPA and ONR.

I. Robotics Mechanisms and Control

   Principal Researchers: Hollerback, Seering, Mason, Pubrick, Salisbury,
                           Asada, Lorenzo Perez, Brooks, Hillis,

   Manipulation

       Design of Dexterous Hands

       - Tendon-actuated three-fingered hands (for use with PUMA) lighter,
         nimbler, more compliant.

       - Controllers for tendon-actuated fingers and shoulders.

       Manipulator Design

       - Direct drive actuation

       - Developed a recursive Lagragian formulation of the dynamics of
         manipulators.

       - Developed a simulation for robot linkages and biological arms.

       - Hybrid controller that allows the available degrees of freedom to be
         divided into position servoing and force feedback servoing as needed
         to achieve the compliance required for assembly and operation under load.

   Perception

       Force and tactile sensors for automating compliant assembly task.

       - High resolution tactile sensor.

       - Strain gage force sensor.

   Programming and Intelligence

       Developing a high level language based on a geometric modeling system
       developed at the AI Lab.

       - Allows errors to be modeled, as well as keeping track of spatial relation-
         ships in ways programmers find natural.

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- Connecting a PUMA directly to a LISP machine to be able to program it
  in this geometric modeling language - to improve robot speed, accuracy
  and interfacing with sensors and effectors.

II. Robot Vision for Parts Assembly and Repair

Principal Researchers: Brady, Grimson, Horn, Larson, Nishihara, and Poggio.

Perception

Acquire possibly overlapping laminar workpieces off a textured background.

- Real time edge detection carried out in hardware using a camera developed
  at M.I.T.

- M.I.T. constructed frame grabber provides a interface to commercially
  available area array cameras for real time processing of image files.

Utilize 3D vision for guiding the acquisition of objects from a bin of
parts.

- Photometric stereo to determine local surface orientation.

  (1) Using multiple light sources and assuming Lambertian reflectance.

  (2) Use of diffuse light sources to determine layout of scences containing
       specular objects.

- Binocular stereo vision utilizing matching of detected edges to obtain
  depth.

Table 8B-2

Institution: Mechanical Engineering Dept., M.I.T.

Principal Researchers: Thomas B. Sheridan, Nam P. Suh, Nathaniel H. Cook, Neville Hogan, (10 grad. students)

Research Funding: Approximately $500K/Yr. from NOAA, ONR, NSF and NIHR.

I. Use of Robotics (Teleoperators) Underseas

   Manipulation

   Teleoperators under computer control.

   Perception

      Tactile sensing for oceanbottom operations.

      Measurement arm attached to base of robot to subtract out base motion.

      Vision tradeoffs of video frame rate, resolution and number of gray scale levels.

II. Upper Extremity Prosthetics

      - movement control

      - adaptive control stiffness

Table 8C

INSTITUTION: Robotics Institute, Carnegie-Mellon University

DIRECTOR: Raj Reddy

RESEARCHERS: 15 Faculty
                 6 Research Associates
                18 Graduate Students
                23 Staff

RESEARCH FUNDING: Approx. $4 M/year from Westinghouse, Digital
                  Equipment Corp, ONR, DARPA, NSF, and other
                  industrial sponsors.

Manipulation

    - Direct drive rare-earth magnet electric actuators for manipulator joints
    - Multi-processor control systems
    - Dexterous end effectors for handling compliant parts

Perception

    - Laser range sensor
    - Proximity sensors
    - Binary and gray scale image analysis and understanding
    - Touch, force, pressure, vibration, temperature, and chemical sensors
    - 3D sensors

Mobility

    - Mobile cart
    - Gait and legged motion analysis

Manufacturing

    - Factory of the Future Project
          - integrated factory system
          - research testbed for manufacturing problem
    - Intelligent Factory Management System
          - Job-shop planning and scheduling
          - Factory modelling and analysis
          - Flexible user interfaces
    - Flexible machining
          - multiple robot and machine integration and control
    - Flexible Assembly
          - multiple robot and sensor integration and control
          - multiple processor controllers
          - electronic assembly

Programming and Intelligence

    - Knowledge representation
    - Problem-solving techniques for planning and scheduling

Table 8D

Institution: Rhode Island University

Principal
Researchers: John Birk
Robert Kelley

Research Funding: Approx. $200 K/yr. from NSF
Approx. $1 M/yr. from Industrial Associates

Manipulation

- Dexterous end effectors

- Articulated hands (includes manipulation within the hand itself).

- Design methods for hands

Perception

- Visual Pose estimation

- Touch sensing

Programming and Intelligence

- Robot programming language

Manufacturing

- Successfully demonstrated bin-picking

- General methods to enable robots with vision to acquire, orient and
transport workpieces

- Design of production systems utilizing robots

Table 8E

Institution: University of Florida

Principal
   Researcher: Del Tesar (+10 faculty from 5 disciplines
                            and 20 grad. students)

Research
   Funding: Approx. $1 M/yr. from DOE, NSF and State of
               Florida

Manipulation

- Human augmentation with real-time digital computer assistance
    (computer-based teleoperators)

- Robot geometry, kinematics and dynamics – to achieve high-level
    dexterity

- Control of structurally flexible manipulators

- On-line robot precision under load (for batch processing)

- Actuator modules – to enable construction of customized manipulators

Programming and Intelligence

- Hierarchical control in an unstructured environment – using force feedback
    assistance.

Table 8F

Robot Research at Other Universities

University	$ Yearly Funding	Manipulation, Perception, Mobility	Programming and Intelligence	Manufacturing
Purdue	100K NSF	• Robot Vision	• Robot Control System • Robot Programming Languages	• Modeling of parts flow thru in industrial plants
U. of Mass	300K NSF			• Design of parts for automatic assembly • Economic application of assembly robots
U. of Mich	500K State of MI	• To Implement a new Robot Lab		
U. of MD		• Robot Vision		
U. of Rochester	200K NSF,ONR	• Machine Vision	• Computer graphics language – PADL	• Automated Manufacturing
U. of Arizona	100K	• Teleoperators		
Ohio State (Robert McGhee)	1M NSF & DARPA	• Legged locomotion	• Manipulator Dynamics and Controls	
U. of IL U. of PA U. of WA U. of Texas R.P.I.		• Small projects in robotics and related work		

dexterity, improved sensory perception, higher-order robot programming languages, increased robot intelligence, and computerized manufacturing and assembly. As indicated in Table 9, the focus of robotics research in the U.S. non-profit research laboratories is on manufacturing, with emphasis on computerized planning, factory management, assembly and inspection.

Table 10 indicates robotic research efforts in commercial U.S. companies. The emphasis is on manufacturing, assembly and computer vision for part recognition and inspection.

Information on research and development in some of the U.S. companies specializing in sophisticated computer vision is indicated in Table 11. The emphasis is on vision for inspection and robot control, and on simplified command capability.

Table 12 gives an indication of the research activities of the principle U.S. robot manufacturers. Emphasis is on advanced control systems, improved programming techniques and mechanical design.

Though there is no central focus for robotics in the U.S. Government, several government agencies are involved in robotics research and a number of others are looking into applications.

Table 13 (roughly reflecting FY-82 funding) provides an overview of robotics research performed within the U.S. Government. In general, these activities can be viewed as exploratory research into robotic applications.

Table 14 presents an overview of robotics research (roughly reflecting FY-82 funding) supported by the U.S. Government. NSF primarily supports basic research, ONR supports a mixture of basic and applied research, while the V.A. is focussed on potential applications for the handicapped.

Table 15 (again roughly reflecting FY-82 funding) indicates some of the government supported robotics applications development in the manufacturing and rework areas.

The various U.S. military services are considering future robotic research efforts that could lead to replacing humans, or leveraging their capabilities, for dangerous jobs or missions and for increased productivity.

It is estimated that the current (FY-82) overall U.S. Government support for robotics research and development is approximately 18 million dollars per year.

Research in Europe and the Soviet Union

The Western Europeons are estimated to be spending two to four times as much as the U.S. on robotics and related research. (A recent survey of teleoperator and robotics research in Europe indicates that $10 million per year is being spent in telemanipulation R&D alone, (Plantier and Bodmer et al., 1981, p. 8).) As in the U.S., the emphasis is on making robots more intelligent and versatile. "Germany, Italy, Sweden, France, Switzerland and the United Kingdom, either in national research laboratories or in robot manufacturers, are presently the most advanced European countries in computer vision and sensor-based robots" (Plantier and Bodmer et al., 1981, p. 12).

No figures are available on robotic research in the U.S.S.R. and the Eastern Block Countries, but they appear to be making a strong effort in robotics in order to improve productivity and overcome labor shortages. However, the Soviets lack of ready access to digital and computer circuitry is hindering their research effects in advanced robots (Teschler, 1981, p. 48).

Table 9A

Robotics Research

Non-Profit Lab: Charles Stark Draper Lab, Inc.

Principle
  Researchers: Jim Nevins
                  Dan Whitney

Research Funding: Approx. $1 M/yr. from NSF and Industry

Manufacturing

- Part-mating science for assembly operations

    - Sensory feedback

    - Adaptive learning

    - Passive compliance

    -Models of assembly process

- Economic and configuration modeling for making choices
  among competing technologies in designing industrial
  systems

- Flexible assembly system design

- Operational strategies

- Product design for producibility

Applications, with industry, range from precision products with
low annual volume to products with annual volumes in excess of several
million. Techniques developed are also applicable to other environments,
such as space, underwater, and medical.

Table 9B

Robotics Research

Non-Profit Lab: SRI International

Principal
  Researcher: David Nitzan

Research Funding: Approx. $1 M/yr. from NSF and
                   Industrial Affiliates

Perception

  • Machine vision for inspection and recognition

  • Robot vision involving structured light, a combination of
    binary and gray-scale vision, and local features to
    distinguish overlapping parts

Manufacturing

  • Vision-guided arc-welding

  • Printed circuit board inspection

  • Programmable assembly

Table 10

Robot Research in Commercial U.S. Companies

Company	Research Activities
GM Warren, MI	• Robot vision systems for inspection and part transfer (KEYSIGHT, CONSIGHT) • Automatic small parts assembly
GE Schenectady, NY	• Flexible computer-controlled high-speed precise assembly, to handle different versions of a one product family from a data base • Evaluation of existing robots for use in GE manufacturing
Westinghouse Pittsburg, PA	• Robotics Research Laboratory evaluating use of commercial robots • Supports productivity research at CMU ($1M/yr.) • Adaptable Programmable Assembly System (APAS) ($1M/yr), cost-shared with NSF • Supports Research on Teleoperators for Nuclear Power Plants at U. of Florida
IBM	• Developed own robots for its manufacturing operations • Developed robot programming languages - AUTOPASS and EMILY
Texas Instruments	• Developed own robot for assembly and testing of hand calculators
Martin Marrietta Denver, CO ($3M/yr.)	• Robotics research directed at DOD and NASA interests - Autonomous devices - Automated diagnosis/checkout - Speed requirements of space manipulators - Simplified high-speed coordinate transformations - CAD robot program planning system • Two arm coordinated manipulation (for DOE)

Table 11

Near-Term R&D in Sophisticated Computer Vision Systems

Automatix
  Burlington, MA

- Robot Vision

- Robot Microcomputer Control Systems

- Robot Programming Language (RAIL)

- Commercial Robot Applications – arc welding

Machine Intelligence
  Corp.
Sunnyvale, CA

- Computer Vision Systems for Turnkey Inspection

- Materials Handling and Assembly Systems

- Univision System developed in cooperation
  with Unimation for the PUMA robot – programmed
  in VAL robot language. This is the first
  commerically-available seeing robot.

- Research in person/robot communication for
  non-computer oriented people.

Table 12

Research Activities of U.S. Robot Manufacturers

Unimation

- Advanced control systems

- Calibration techniques

- Programming techniques

- Mobility systems

- UNIKA™ vision for arc welding

Cincinnati Milacron

- New control system architectures

- Programming language

- Mechanical design

Other Robot Manufacturers

- Similar activities - all aggressively developing new and
  improved product lines.

Table 13

In-House Government Robotic Research

Organization   Research Activities

National Bureau   Standards
  of Standards
  $1-1/2 M/yr.   • Robot Interface Standands

                             • Robot Performance Measures

                             • Programming Language Standards for

                                  - robot systems
                                  - integrated computer-aided manufacturing

                           Advanced Concepts for

                             • sensory-interactive control systems

                             • modular distributed systems

                             • sensor interfaces to the control systems
                               of robots and machine tools

                             • vision systems

                           Focussed Application

                             • Automated Manufacturing Research Facility

                                  - planning
                                  - scheduling
                                  - routing
                                  - inspection
                                  - demonstration of a completely automated
                                      machine shop consisting of computer
                                      controlled NC machines served by
                                      robots and robot carts, producing
                                      mixed configurations of parts on
                                      demand

Table 13 (cont.)

In-House Government Robotics Research

Organization	Center	Activity

NASA
$1M/yr.
12 man years
	Langley Research Center
	Hampton, VA
		• Robotics Laboratory to develop teleoperated and automated spacecraft servicing techniques
		
		  – Trajectory planning and multi-arm coordination
		
		  – Man-machine interface for remote systems
		
		  – Operating system for concurrent processes in a distributed computer network
		
		  – Robotics simulation

	Marshall Space Flight Center Huntsville, Ala.	• Research on end-effectors • Man-machine interface for teleoperation
	JPL Pasadina, CA	• Research in Hand-Eye Coordination • Control of structurally-flexible manipulators • Teleoperators . • 3 fingered hand with Stanford U.

Naval Ocean Systems
  Center
San Diego, CA
$650K

Exploring application of robot and teleoperator systems

• submersibles
• land vehicles
• underwater manipulators
• stereo optic and acoustic vision
• remote presence
• autonomous robots – knowledge representation and automatic decision-making
• complex robot systems specification and verification

Table 13 (cont.)

In-House Government Robotics Research

Naval Ocean Systems Center Hawaii $300K	Exploring the use of telepresence (teleoperation with sensory feedback directly to the operator, giving a sense of being at the work site) for use in materials handling aboard ship.

Table 14

U.S. Government Supported Robotic Research

Organization: NSF
Washington, D.C.

Program (FY-81)	Organizations Supported and P.I.		Activity
Production Research $2M (W. Spurgeon) (Emphasis on robotics for assembly)	U. of R.I.	– Birk	Part acquisition using vision
	C. N. K. Corp.	– Hayes	Part Recognition
	SRI	– Barnard	Auto. Visual PCB inspection
	SRI	– Nitzan	M.I. applied to Industrial Auto.
	Merrick Corp.	– Cook	Adaptive arc welding
	Taylor Sys. Engr.	– Kerth	Adaptive arc welding
	Stanford U.	– McCarthy & Binford	Integrated Programmable Auto.
	M.I. Corp.	– Rosen	Natural Language
	U. of Mass.	– Boothroyd	Economic applications
Mechanical Systems (A. Strauss) $700K (Emphasis on control, dynamics, kinematics, and design)	U.C. Berkeley	– Tomizuka	Digital Control of Industrial Process
	"	– Dornfield	Control of arc welding
	UCLA	– Dubowsky	Dynamics of high speed machines
	U of FL	– Sandor	Kinematic analysis
	"	– Hole	Nonlinear dynamic structual synthesis
	U. of Nebraska	– Schade	Mechanism motions
	Rutgers	– Lee	Design of high speed mechanisms
	Stevens	– Tricano	Optimum design of mechanisms.
	Columbia	– Freudenstein	Forces in high speed linkages
	Ohio State	– Srinivasan	Control of machine tool feeds
	U. of Conn.	– Huston	Multi-body dynamics

Program (FY-81)	Organizations Supported and P.I.		Activity
Automation, Bio-engineering and Sensing Systems $750K (Emphasis on robotics vision and intelligent controls)	U. of PA	– Rozina	Scene understanding
	Purdue	– Kashyap	Image modeling
	CMU	– Sanderson	Parallel signal processing
	SUNY	– Shapiro	Edge detection in images
	U. of S. Carolina	– Cannon	Auto signal processing
	U. of IL	– Ahuja	Dot pattern processing
	Purdue	– Funkunaga	Image feature evaluation
	U. of Minn.	– Wechsler	Texture analysis
	U. of IL	– Gose	Auto. scene analysis
	RPI	– Saridis	Intelligent controls
	Yale	– Narendra	Self-learning systems

Table 14 (cont.)

U.S. Government Supported Robotic Research

Organization: NSF
Washington, D.C.

Program (FY-81)	Organizations Supported and P.I.		Activity
Public Technology (A. Schwarzkopf) $450K	Westinghouse	– Abraham	Programmable assembly
Computer Engineering (B. Chern) $300K	U. of Rochester	– Voelcker & Requicha	Geometric modeling
	CMU	– Chang	Robot memory
Intelligent Systems (Y. T. Chien) $100K	VPI	– Shapiro & Haralick	Geometric reasoning
	U. of PA	– Bajczy	Scene understanding using active sensing

Table 14

U.S. Government Supported Robotic Research (cont.)

Organization	Organization Supported	Activities
Office of Naval Research Arlington, VA $1.7M/yr. (Marvin Denicoff)	M.I.T. $700K/yr.	• Fundamental research in - vision - manipulation - reasoning
	CMU $700K	• Autonomous Unmanned Underwater Vehicles
	SRI $250K	• Communication and negotiation among distributed robots
	U. of Rochester $100K	• Machine Vision
Defense Advanced Research Projects Agency Arlington, VA (Robert Kahn) $300K/Yr.	M.I.T. $300K	• Fundamental research in robotic vision, manipulation and reasoning (in cooperation with ONR)
Veterans Administration Washington, D.C. (Dr. Margaret Gianni) $400K/yr.	Applied Physics Lab John Hopkins Univ. $100K	• Robotic work station for quadriplegics
	Rehabilitation Engr. Center Stanford Univ. $200K	• Robotic aids for severely disabled individuals
		• Supervisory voice and head-orientation command of a PUMA robot
		• Human/Machine Interface
	VA Hospital – West Roxbury $50K	• Myographic wheelchair control
	VA Hospital – White River Junction, N.H. $65K	• Communication control aid

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Table 14 (cont.)

Organization	Program	Organizations Supported & P.I.	Activity
A.F.O.S.R. (A.F. Off. of Scientific Research) Bolling AFB, D.C.	Manufacturing Science (Tom Walsh) $2 M/yr.	Developing Educational Research centers of excellence	• Assembly in manufacturing

Table 15

U.S. Government Robotic Applications Development

Organization	Activity

Naval Air Rework Facility
San Diego, CA
$3 M/yr.
	• Development of robots to
	
	  – remove rivets and fasteners from
	    airplane wings
	  – strip and repaint aircraft
	  – perform wing assembly

Air Force Materials Lab. Wright Patterson AFB Dayton, Ohio $1M/yr.	• Robotic applications in manufacturing (Part of ICAM)
U.S. Army Human Engr. Lab. Aberdeen Proving Grounds, MD	• Formulating a plan for military applications of robotics
Office of Manufacturing Technology DARCOM	• Robot applications in manufacturing

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XVI. Applications Now and in the Future

Figure 9 indicates current and anticipated future use of robots in manufacture
in Japan. Currently, machine tool processing is dominant, followed by welding,
assembly, and plastic molding. In % of value, assembly, and measurement and
inspection are expected to increase while spot welding, plastic molding and
machining processes are expected to decrease.

Table 16 indicates current and 1990 estimates of major uses for industrial
robots in the U.S. In general the same trends are visible in the U.S. as in Japan,
with welding and materials handling being currently dominant, moving towards
assembly being the dominant application in 1990.

A recent JIRA forecast of robot applications development, introduction and
diffusion is shown in Figure 10. Observe that by 1985 it is anticipated that robots
for assembly, inspection, reactor maintenance, cleaning and ocean development, as
well as all phases of manufacturing, will be in commercial use, with diffusion
relatively complete by 1990. In the last half of this decade it is forecast that
construction and mining robots, robots for fire fighting and even robots to assemble
soft goods like textiles will begin commercial diffusion. In the same time period,
prosthetic arms and legs, and robots for use in patient care and other medical
applications will become widespread.

In the late 1980's, robots for use in various military applications, such
as use in dangerous missions and hostile environments are also expected to appear.
Also in the late 80's, robots for use in servicing of space satellites are anticipated.
In the 1990's, robots for use in the construction and assembly of large space
structures and in space manufacturing are forecast. Starting around 1995, semi-
autonomous robots are foreseen for use on extra terrestrial surfaces for exploration,
mining, materials processing, manufacture, and the construction, tending and
maintaining of space installations.

Figure 9

JIRA Forecast of Japanese User Needs
for IR's by Production Process
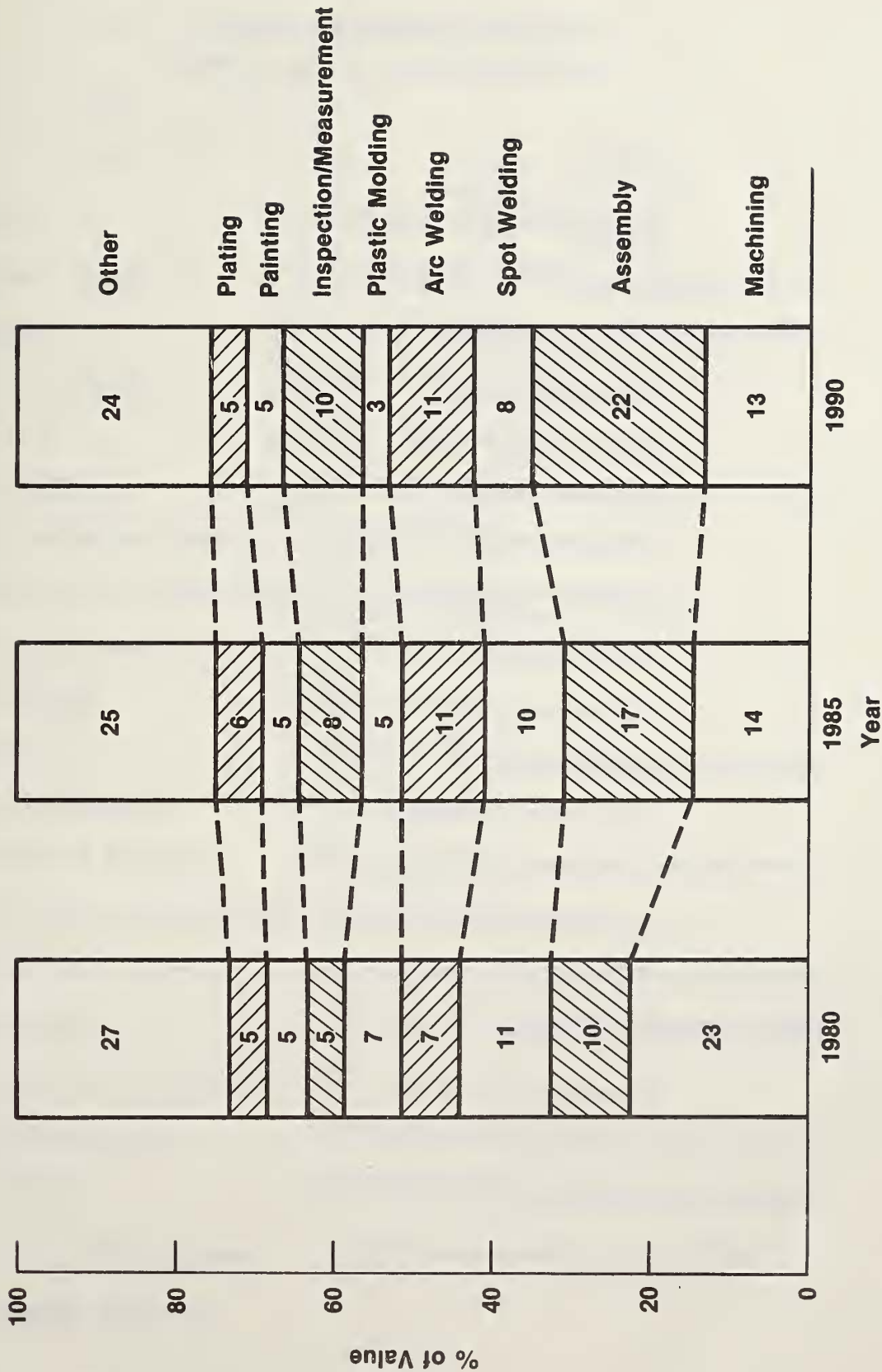
Source: Research Div. of the Long-Term Credit Bank of Japan, 1981, p. 74.

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Table 16

Estimated U.S. Robot Order Trends By Usage

	Through 1981	1990
Materials handling, including machine loading and un-loading	25-30%	30-35%
Assembly	10%	35-40%
Spot-Welding	35-45%	3-5%
Arc-Welding	5-8%	15-20%
Paint spraying	8-12%	5%
Other	8-10%	7-10%

Source: (Conigliaro, 1981, p. 6)

Figure 10

Robot Development, Introduction and Diffusion
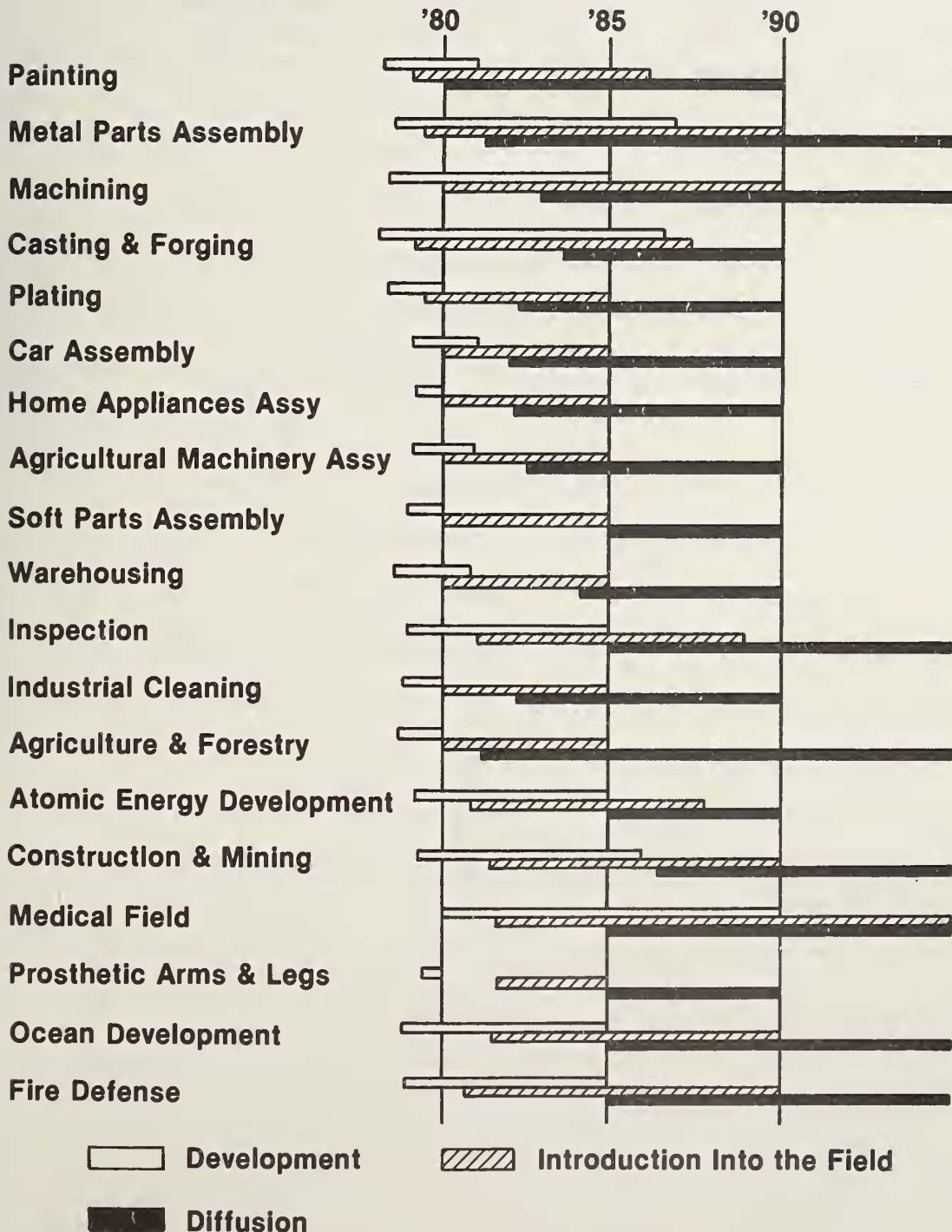
Source: JIRA (Hasegawa, 1981, p.171)

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The general trend is toward robots with ever increasing intelligence and sensory capabilities. Engelberger (1980, p. 135) suggests that robots will eventually be entering the service industries, with such diverse applications as garbage collection and fast food preparation and dispensing. He even suggests that "...a [limited] household robot may be practicable before the end of the 1980's decade."

XVII.   The Expanding Robot Population

Table 2 presents JIRA's (The Long-Term Credit Bank of Japan, 1981, p. 52) estimate of the world's robot population as of the end of 1979. The figures shown are for high-quality robots and exclude manually manipulated robots (tele-operators) and fixed sequence robots. Note that Japan with 14,000 robots has nearly 70% of the world's total, compared with 16% (representing a little over 3,000 units) for the U.S.

Figure 11 projects the U.S. robotics industry growth through 1990, when it is estimated that the U.S. will have roughly 100,000 IR's in operation, or some 30 times that of 1979. This estimate is predicated on major diversified companies - such as GE, Westinghouse, GM and IBM - entering the market as now appears to be happening.

Table 17 presents JIRA's forecast for the production of IR's in Japan through 1990, while Figure 12 indicates how this production will be distributed.

Integrating the results from Tables 2 and 17 and Figure 11, Figure 13 presents the composite forecast of the industrial robot population through 1990. It appears that the world's robot population will pass 1,000,000 in the early 1990's, and will therefore have a major impact on the world's productivity.

A recent article in Business Week (Dec. 14, 1981) indicates that the robot pace is continuing to accelerate and even the figures quoted here may be very conservative.
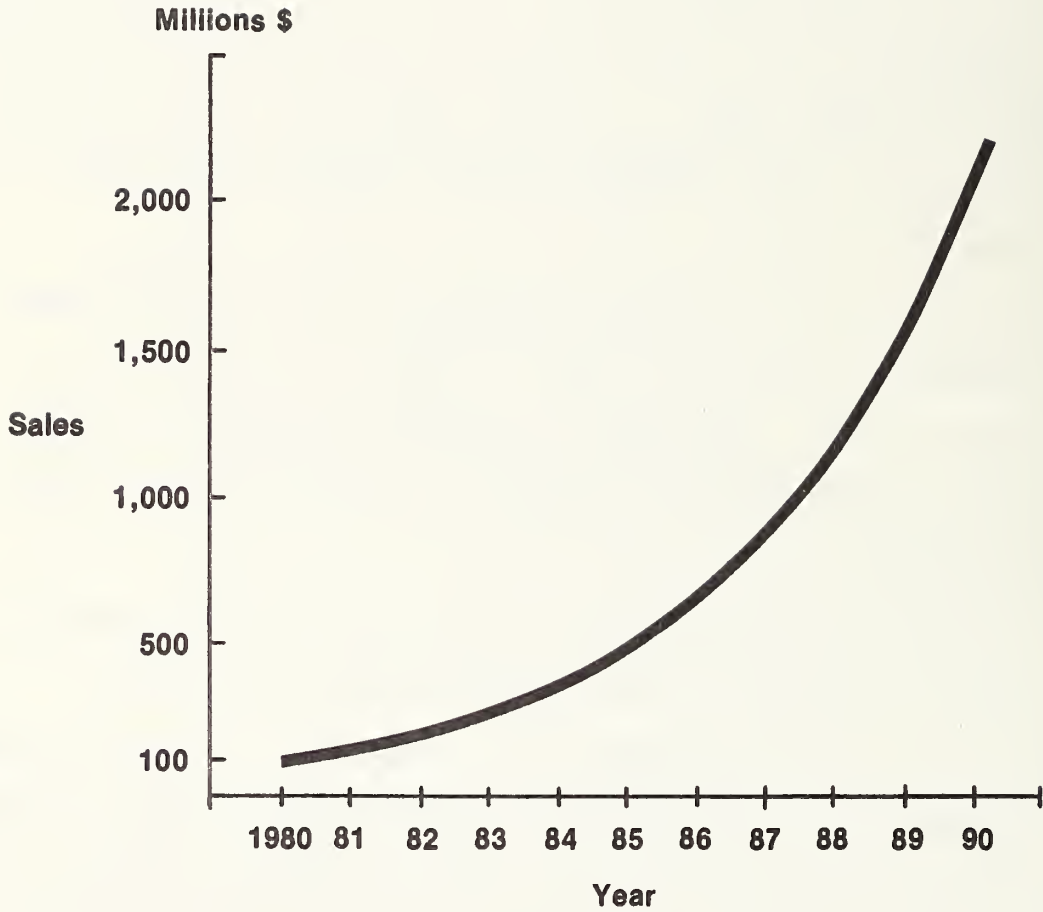
Figure 11

**U.S. Robotics Industry Growth
1980-1990**

Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Estimated Sales ($ Millions)	$ 100	150	215	280	395	540	725	875	1125	1520	2070
Estimated Units Sold		1450	2100	3075	4000	5600	7715	10350	13000	17000	23000	31350

(Assumed Avg. Robot Cost Approx. $70K Each)

Compound Growth of Revenue Per Year: 35%

Table 17

Forecast of Aggregate Demand in Manufacturing for All Classes of
IRs in Japan

(Unit $ Billion)

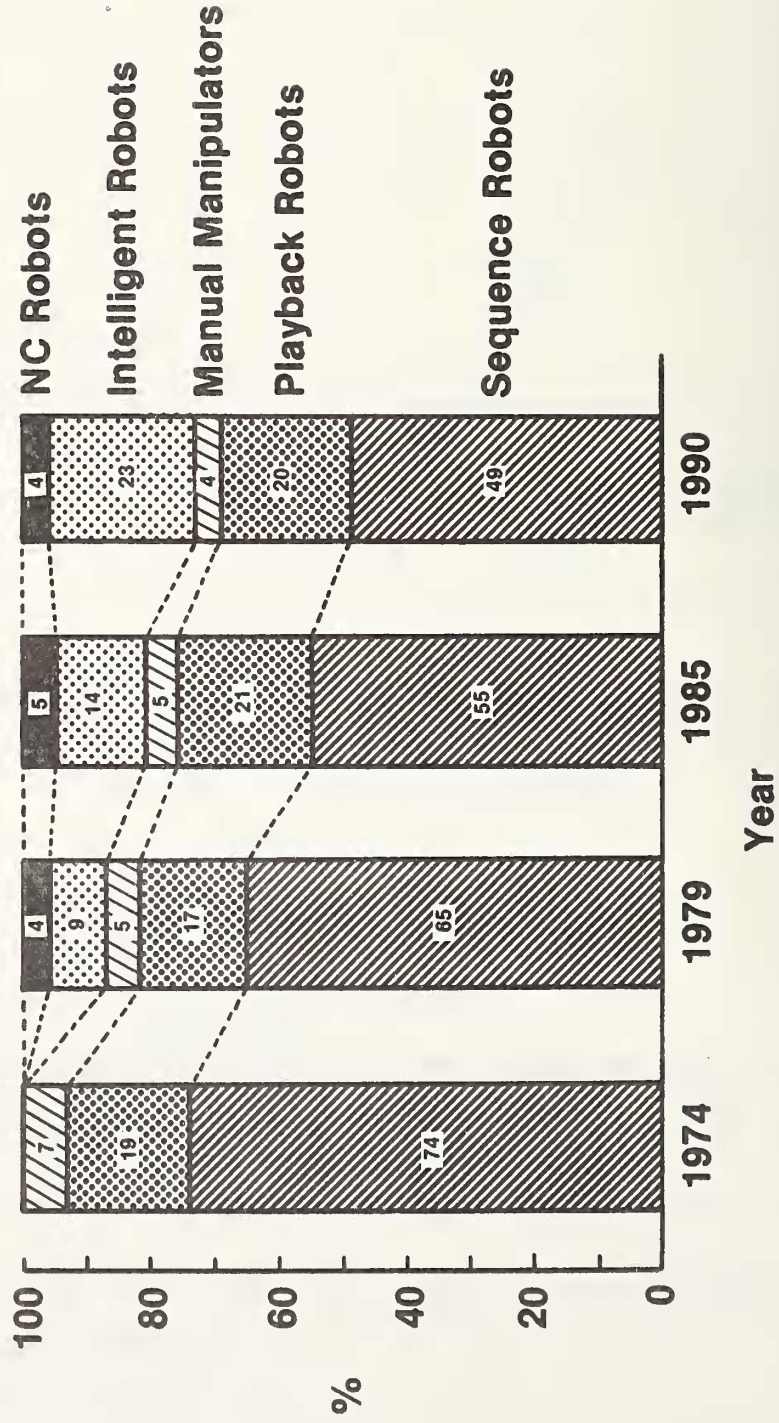|	1980	1985	1990	Annual Growth Rate 1985/1980	1990/1985
Domestic Demand	0.3	0.8 to 1.1	1.6 to 2.2	30%	14%
Exports	Negli-gible	0.2	0.4	-	15%
Total	0.3	1.1 to 1.3	2.0 to 2.7	35%	14%
Annual Production (Thousands of Units)	19.7	43 to 55	75 to 94	-	-

(Note) The export ratio is based on the JIRA target value of 20% in 1990.

Source: The Long-Term Credit Bank of Japan, 1981, p. 69.

Figure 12

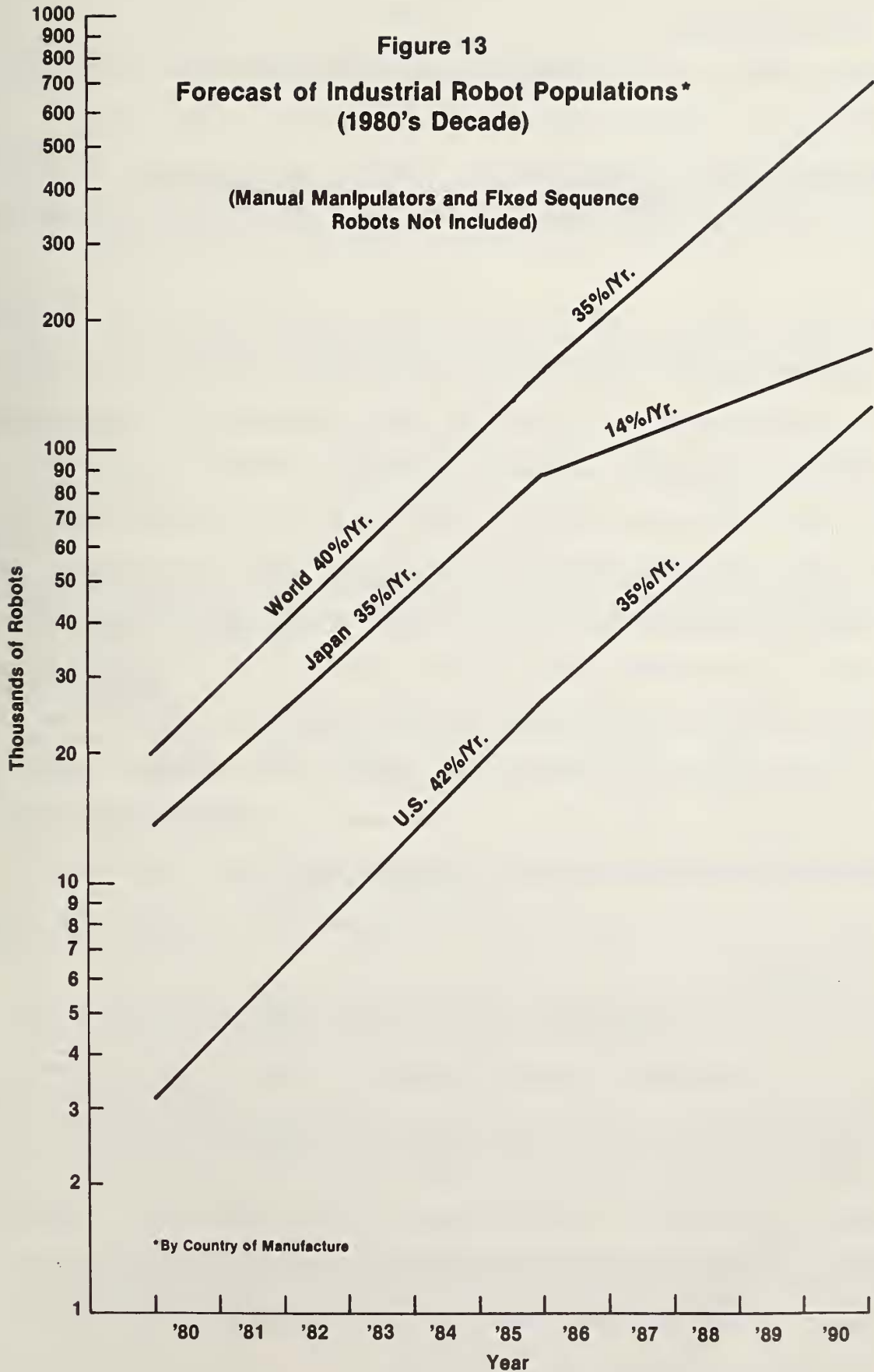## JIRA Estimate of Composition of IR Production in Japan (Based on Value)

NC Robots

Intelligent Robots

Manual Manipulators

Playback Robots

Sequence Robots

Year

%

Figure 13

Forecast of Industrial Robot Populations*
(1980's Decade)

(Manual Manipulators and Fixed Sequence
Robots Not Included)

*By Country of Manufacture

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XVIII. Future Directions

Hasegawa (1981, pp. 169-170) makes the forecast of unfolding robot technology given in Figure 14. Based on these technological trends, he states that "...industrial robots will become smarter, smaller, quicker, lighter, stronger, more ingenious, easier to operate, more intelligent and less expensive that they are now."

Engelberger (1980, p. 118) lists in Figure 5 the qualities sought in future robots. He indicates that these qualities will be, for the most part available during the current decade. Of the missing robotic attributes, he considers the two crucial ones to be vision and tactile sensing.

JIRA (The Long-Term Credit Bank of Japan, 1981, p. 59) indicates that the technology for robot miniaturization, modularization, high speed operation, and computer control has advanced to the point where it is now available and will grow in popularity and acceptance in the first half of this decade. Technology for part recognition and position determination is also currently available, but won't receive widespread popularity until the second half of this decade. Technology for color and behavior recognition, automated assembly, and machine tool and casting robotics won't become adequately advanced until later in the first half of the decade and therefore won't achieve widespread popularity until the second half of the 1980's.

One of the greatest advantages of robotics and automation occurs in the cases where their use greatly increases equipment utilization. Albus (1981B) indicates that a robot arc welder cannot weld faster than a human, but by keeping its torch on the work about 90% of the time, versus no more than 30% of the time for a human, it can turn out 3 times as much work in the same time. If through automation more shifts can be worked, productivity is even further increased. Unfortunately, present day robots cannot set up their own work, so this reduces their productivity advantage. Albus conjectures:

Figure 14

Forecast of Robot Technology

° Materials

    Lighter and stronger materials for robot structures will be developed.
    These will include both organic and non-organic substances. As a
    consequence, the size and weight of robots will decrease.

° Power Sources

    Small, high-capacity power sources such as nuclear powered generators or
    fuel cells will allow robots greater freedom of location and movement.

° Actuators

    Small, high performance actuators will appear. Robot designs will be
    more stylish.

° Sensors

    Small, reliable, high-performance, low-cost artificial eyes, ears, and
    tactile sensors will be developed and even low-cost robots will have
    recognition capability.

° Control Systems

    Advances in microcomputer technology will dramatically improve robot
    control. Control system costs will also be greatly reduced.

° Communications Systems

    Remote control of industrial robots will be enhanced through development
    in fiber optics, wireless communcations, etc.

° Processing Methods

    New, non-mechanical processing methods such as laser beam cutting,
    welding and other high-energy processing methods will reduce the processing
    load on robots and make the design work for them simpler.

° Robot Body Structure

    Utilization of biomechanical concepts will result in superior robot
    structures.

° Software

    Robot use will become easier through the development of robot languages,
    self-diagnosing systems and robot application technologies. Software
    will contribute to reducing the design work needed on robots.

Figure 14 (cont'd)

° Integrated Systems

Techniques for integrating production systems composed of men, machines and robots as well as their peripheral devices will be found. Further, their design processes will be computerized.

Source: Hasegawa, 1981, pp. 169-170.

Eventually, welding robots will be sufficiently sophisticated to work from plans stored in computer memory and to correct errors which may occur during a job. Welding robots will then be able to work nights and weekends (four shifts per week) completely without human supervision. At that point productivity improvements over present methods of many hundreds of percent become possible. Unfortunately, we are a long way from that today. There are many difficult research and development problems that must be solved first. Unless the level of effort in software development is increased many fold, these improvements will not be realized for many years.

In the metal cutting industry, Albus (pp. 16-18) predicts,

During the 1980's, robot sensory and control capabilities will improve to the point where robots can find and load unoriented parts, or in some cases, even pick parts out of a bin filled with randomly oriented parts lying on top of each other. This may improve productivity by hundreds of percent because it will make it possible to install robots in many existing plants without major re-engineering of production methods....

By 1990 robots may begin to have a significant impact on mechanical assembly. There has been a great deal of research effort spent on robot assembly. Unfortunately, the results have not been spectacular--yet. On the one hand, robots cannot compete with classical so-called "hard automation" in assembly of mass produced parts. General purpose machines like robots are still too slow and too expensive to be economical for mass production assembly tasks. On the other hand, robots cannot yet compete with human assembly workers in small lot assembly. Humans are incredibly adaptable, dexterous, as well as fast, skilled, and relatively cheap compared to robots...

Nevertheless, progress is being made and will continue. Robot capabilities will gradually increase. Sensory systems will become more sophisticated and less expensive. The cost of computer hardware is dropping rapidly and steadily with no sign of bottoming out. Software costs are likely to be the major impediment to robot development of the foreseeable future, but even these are slowly yielding to the techniques of structured programming and high level languages.

Eventually, extremely fast, accurate, dexterous robots will be programmed using design graphics data bases which describe the shape of the parts to be made and the configuration of the assemblies to be constructed. Eventually, robots will be able to respond to a wide variety of sensory cues, to learn by experience

and to acquire skills by self optimization. Such skills can then be transferred to other robots so that learning can be propagated rapidly throughout the robot labor force.

Sometimes, perhaps around the turn of the century, robot technology will develop to the degree necessary to produce the totally automated factory. In such factories robots will perform most, if not all, of the operations that now require human skills. There will be totally automatic inventory and tool management, automatic machining, assembly, finishing, and inspection systems. Automatic factories will even be able to reproduce themselves. That is, automatic factories will make the components for other automatic factories.

Once this occurs, productivity improvements will propagate from generation to generation. Each generation of machines will produce machines less expensive and more sophisticated than themselves. This will bring about an exponential decline in the cost of robots and automatic factories which may equal the cost/performance record of the computer industry...

Eventually, products produced in automatic factories may cost only slightly more than the raw materials and energy from which they are made.

In summary, what we see emerging are robots with increasing intelligence, sensory capability, and dexterity. Initially, we will see an increasing use of off-line programming of computer-controlled robots, using improved robot command languages. Provision will be made to include the role of sensors, such as vision and touch, in this programming. Later, self-planning will emerge as higher and more general commands are given to the robot. At this point, the marriage of robotics and artificial intelligence will be virtually complete. At the same time as all this is taking place, robotic hands with improved dexterity (so that it will not be necessary to move the entire arm for fine motions), and advanced control systems to support this dexterity, will emerge. Also emerging will be robots with coordinated multiple arms and eventually even legs, supported by even more sophisticated control systems.

As this evolution progresses, information and intelligence will become the dominant factor in robotics, with the manipulator devices and sensors shrinking in importance to the skeleton that undergirds this dominating "ghost in the machine".

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This report provides an overview of the rapidly changing field of robotics. It is intended to be read by the technically oriented layman, such as engineering managers, government funding offices, and others who desire an overall perspective of the field but are unable to obtain it from the highly technical and unintegrated literature in the field, or from the more flamboyant but non-technical feature articles in the popular press.

The report incorporates definitions of the various types of robots, a summary of the basic concepts utilized in each of the many technical areas, review of the state-of-the-art and statistics of robot manufacture and usage. Particular attention is paid to the status of robot development, the organizations involved, their activities, and their funding. A 5-10 year forecast of the emerging technology is also included.

The majority of the material in this report is drawn from the activities in the U.S. and Japan, the principle players in the world of robotics.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)
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