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TECHNOLOGICAL FORECASTS

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The fact is that civilization requires slaves. The Greeks were quite right there. Unless there are slaves to do the ugly, horrible, uninteresting work, culture and contemplation become almost impossible. Human slavery is wrong, insecure, and demoralizing. On mechanical slavery, on the slavery of robots the future of the world depends. (1)

INTRODUCTION

Robotic technology is becoming increasingly important in manufacturing, work in space, undersea work, nuclear industry, medicine, and almost all areas where machines enter society. In many industrial applications it has been demonstrated that use of robotics can lead to increased productivity, more flexibility, lower operating costs, higher reliability, and a reduction in hazards to humans. In general, it is difficult to provide an accurate forecast of robotic technology. Most technology forecasts are based on logical extrapolation of evolutionary growth trends and cannot take into consideration introduction of revolutionary innovations and progress. For instance, until very recently, it seemed that only very sophisticated and expensive machines could incorporate some form of decision making. The situation was, however, entirely changed with the revolutionary growth in computer technology and the introduction of microprocessors. These processors can, rather inexpensively, add decision-making capability to any machine or system.

For these reasons, this article first provides an assessment of present robot technology. The forecast of future robot technology is then presented in terms of extrapolation of present technology to only the next generation of robot technology. This extrapolation incorporates only expected improvements in the present component technologies and expected growth characteristics of the robotic market. The work is also limited to the most common robot manipulators, excluding other types of robotic devices such as walking machines or teleoperators; it is further limited to the U.S. technology base and market.

PRESENT INDUSTRIAL ROBOT TECHNOLOGY

The present-day robot consists of several component technologies integrated into a machine capable of manipulating and affecting objects in its environment. The machine is usually a mechanical device consisting of a manipulator and an end-effector. The function of the end-effector is usually to hold an object or tool. The manipulator is used to maneuver the object or tool relative to the base of the robot. The manipulator differs from most traditional machines in that it has multi-degree-of-freedom and reprogrammable controls. A manipulator can therefore execute a variety of complex motions by reprogramming coordinated control of its various degrees-of-freedom.

In a robot, in addition to a mechanical manipulator and an end-effector, some form of a processing unit or computer is used for decision making and to provide the proper control signals needed for coordinated motion of its manipulator links. Some industrial robots are also equipped with external sensors, which are different from the internal sensors used by robots to monitor their internal state. Robots use external sensors to interact with their environment. Robots also communicate with other machines as well as with human users in their environments through proper data and human-machine interfaces. The operation of an industrial robot, therefore, involves the execution of the following basic functions: manipulation, sensing, communication, control, and processing or decision making. This is shown in functional block diagram form in Figure 1. The first three functions (manipulation, sensing, and communication) involve interactions with the robot environment. The other two functions, however, are internal to the robot itself. These five functions are influenced by the basic components of the robot.

The components of present-day robots can be categorized into four basic groups. These are the manipulation system, consisting of the manipulator and the hand or end-effector; the robot servo drive system, consisting an actuator, the joint feedback sensors, the power transmission mechanism, the controller, and the motion control software; the robot external interfaces, consisting of external sensors and the robot data communication system; and the robot human-machine interfaces, consisting of the user programming system, integrated electronic pictorial displays, etc.

Manipulation System

The manipulation system of a present-day industrial robot consists of a mechanical arm or manipulator and a hand or end-effector.

Most commercially available manipulators are designed with rotary and/or translatory joints, each having a single degree of freedom. The geometric architecture of these manipulators is usually serial (one link, one joint, one link, etc). The joints are also partitioned such that the first few (three) joints closest to the base are used to position a point at the end of the arm. The last few joints (three or fewer) form the wrist, which is usually designed to be used to orient the hand

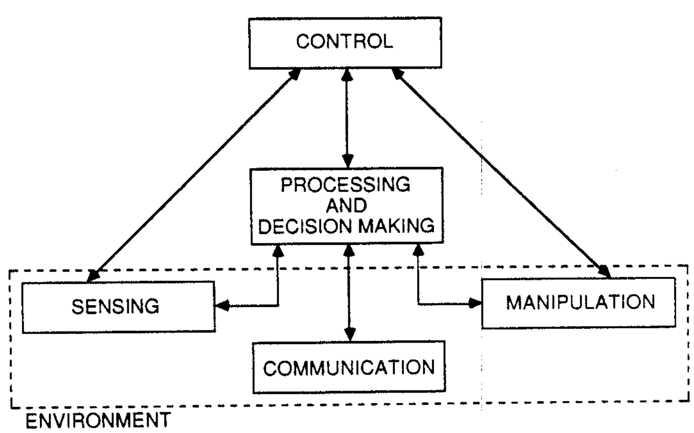

Figure 1. Functional block diagram of a robotic system.

or the end-effector. A well-developed body of kinematic theories (2–4) exists for producing any desired movement of the end-effector for these and similar manipulator geometries. The geometry of the manipulator affects the manipulation function of the robot. The existing wrist-partitioned geometries result in degenerate performances in manipulating objects (5–6) and limit the dexterity and kinematic performance of the robot (7–9). Recently, wrist designs have appeared (see eg 10,11) that allow resolution of the degeneracies and singularities in the kinematics of the wrist. Although efficient computational methods (12–15) for handling kinematics of more general manipulator geometries exist, no commercial system uses them.

The amount of payload (size and weight) that can be manipulated and the precision (16) of the manipulation are also affected by the construction, geometry, and structure of the mechanical manipulators. Most commercially available systems have serial geometric architectures with a payload-to-weight ratio of less than 10%. The manipulator links are also usually made from shell- and beam-type structures. In most such systems, end-point disturbances due to loads equivalent to the specified payload can cause deflection 10 to 20 times the end-point repeatability of the robot. This means that precision light machining operations, for example, cannot be performed by these robots. Recently, some research has been done on the use of composite or fibrous materials (17,18) for robotics applications. These materials, however, have not yet appeared in commercially available systems. In connection with the manipulator, its geometry, structural flexibility, thermal expansion capacity, mechanical and structural clearances and plays also influence the repeatability of the robot. Present-day industrial robots have typical end-point repeatabilities ranging from a few to $\pm 9.8 \times 10^{-5}$in. (± 0.0025 mm). In addition to the manipulator, some of the robot's other components also influence its end-point repeatability, but these are described later.

Most existing manipulators have six or fewer degrees of freedom. Six degrees of freedom are needed to position the end-effector at any location within the workspace of the manipulator. For applications involving arc welding or complex contour tracing only five degrees of freedom are necessary. Robots with four degrees of freedom are also common for many forms of planar contour tracing or pancake assembly tasks. Recently, few systems with more than six degrees of freedom have been built. Such systems generally have better dexterity than systems with fewer degrees of freedom and can, for example, reach around obstacles. Complexity of control and manufacturing costs, however, have limited the offerings of such systems.

There have also been some commercial attempts to provide the equivalent of more than six degrees of freedom through the adaptation of multiple manipulator or multiple arm robots. These attempts have not been overwhelmingly successful, but they are indicative of the efforts to solve such problems as extended dexterity, multiple arm service, and multiple arm coordinated moves.

Most commercial end-effectors are simple two-finger grippers fastened to the free end of manipulators. There is a wide range of commercial end-effector designs with varying levels of sophistication and cost. In addition, many robot applications require custom-made end-effectors to match process requirements. Recent trends in end-effector design have been toward systems with more dexterity and greater flexibility. Some dexterous end-effector designs have appeared in different research laboratories (19,20). However, these end-effectors have not yet been used at the end of manipulators in commercial applications.

Servo Drive System

The servo-drive system of an industrial robot affects both its manipulation and control functions. Present-day robots usually use one of the hydraulic, pneumatic, or electric actuator systems. Hydraulic actuators provide for high load-carrying capacities and high power-to-weight ratios. They are, however, hard to maintain (due to leakage losses), bulky, energy inefficient, and a major source of contamination. Pneumatic actuators have low weights but can only provide simple point-to-point control functions because closed loop positional control is generally difficult to realize for such systems. Pneumatic actuators are, however, good for non-servo control functions requiring fast movements.

Electric actuators are by far the most common of the three types of actuator systems used in commercially available robots. Although d-c motors are the usual choice, stepping motors are sometimes used especially in less demanding applications. Stepping motors have a simpler servo-control system and do not need a position sensor, but they have problems detecting overloads or stalls, resulting in a need for recalibration of the robot every time a motor is stalled or overloaded.

The torque speed characteristics of electric motors available today usually do not match the robot drive needs well. Some form of power transmission device, such as a gear reduction unit, is therefore used between the actuator and each link of the robot. Harmonic drives are the most common type of gear reduction used because of their high reduction ratio and compact size. Ball screws and other types of gear reduction units are also used in many commercially available robots. The transmission device influences both the manipulation and the control functions in a robotic system. The manufacturing tolerances, structural flexibility, backlash, and plays in the transmission mechanism influence the precision with which objects can be manipulated. The control function is also affected by backlash, friction, and motion transmission complexity of the transmission mechanism.

Recently some electric motors have been introduced that eliminate the need for transmission devices. These are d-c motors with high-density, high-energy samarium-cobalt magnets. When these motors are used as robot actuators, the stator is connected to one link and the armature to the next link at the common joint between the two links (21). Another type of direct drive robot has also been developed (30), which uses multi-degree-of-freedom closed loop mechanisms for the kinematic structure of the manipulator and connects the electric motors directly to the independent joints of the closed loop mechanism.

Most electric servo-drive systems in commercially available robots use both position and velocity feedback for their control. Position feedback is usually provided by means of resolvers or optical encoders. Incremental encoders are most commonly used although, in some cases, absolute encoders are used. Velocity feedback is usually in analogue form and is provided by a tachometer attached to the motor shaft. Tachometer feedback adds damping to the position control servo loop. The transducers used for servo control of the joint actuators influence both the control and the manipulation functions of the industrial robots. They are necessary for closing the feedback loop in the servo-control system, and in addition, they affect the precision of the robot. The end-point resolution of the robot is affected by the resolution of the joint encoders or resolvers. The actual joint resolution for commercially available systems varies from one part in 2^8–2^{18} counts for revolute joints and 7.8×10^{-3} to 7.8×10^{-5} in. (0.22 mm to 0.002 mm) for prismatic joints. Industrial robots using absolute joint position sensors, such as absolute encoders, do not need recalibration of the joint position due to shifts in the reference position of the encoder. In addition to the use of position and velocity feedback, some manipulators have also been constructed with internal force servo controllers (23–25). Force servo controllers, however, have not generally appeared in commercially available robots.

The control electronics of the servo control system also influence the robot's manipulation function. Current commercial robots use a relatively simple constant gain linear feedback control system. The fixed servo gains affect robot repeatability, and the resolution of the digital-to-analogue converters affect robot resolution. Present robot controllers can compensate only poorly for nonlinear manipulator characteristics and are insensitive to parameter and environmental changes. Methods for adaptive control (26) and design of robust controllers (27) have been developed recently but have not yet been implemented in commercially available robots.

Motion control software in most commercial robots employs at least joint-level control in the form of trapezoidal velocity profiles. The motion control software affects the manipulation function of the robot. Some current robots are equipped with motion control capability in terms of the world or workspace coordinates. This involves moving a point on the end-effector (the wrist or the tool center point) along a specified path in the workspace. The desired path can be a straight line or several blended straight line segments. The desired path is usually decomposed into a series of short segments. The motion control software then resolves the positions of the end-effector at each of these segment end-points into joint positions using the inverse kinematic solution or an approximation to it. The resulting target joint positions are then used to update the joint servos. The servo response times are matched to the position update rates to ensure smooth and continuous motion. Velocities and accelerations are controlled by varying the incremental distance between successive points. The accuracy of a robot is influenced by the accuracy of the mathematical model used for such trajectory computations. Present-day noncalibrated robots have typical accuracies approximately 10 times worse than their repeatability.

External Interfaces

The external interface component group of present-day robots includes external sensors used by the robot to monitor its environment and the data communication interfaces between the robot and other machines or computers in its environment. These components clearly affect the sensing and the communication functions of the robot. Sensors also affect the manipulation and the control functions of the robot. They enable the robot to improve its manipulation capability, for example, in dealing with inaccuracies in its task information and in recovering from errors. In addition, sensors enable the robot to close its servo-control loop at its end-point, for example, in certain force control applications. The data communication interfaces also affect the manipulation function of a robot but in an indirect way. They allow the robot to work in a cooperative mode with other machines or robots in performing a task.

There are two general categories of external sensors currently used by some robots. These are the contact and noncontact sensors. Contact or tactile sensors can detect touch or measure pressure or force. Some robots use tactile sensors on their fingertips to monitor interactions of the robot hand with the objects being manipulated. Tactile sensors (28) either detect, as when the hand touches something, or measure some combination of force and torque (29) that the hand is exerting on the object. Such information is usually used for proper grasping of the object or in sensor-controlled manipulation, and for error recovery (eg 29). Small tactile arrays that can measure pressure distributions over a planar region of one square inch have recently become commercially available. Such tactile arrays can be used on the fingertip of robot end-effectors. A number of innovative transducers are used in tactile arrays. These involve, for example, using conductive elastomers and rubbers (31,32), carbon fibers (3), and magnetic dipoles (34). A form of multiplexing has also been developed, using VLSI technology (35), to decrease the number of wires required in an array of tactile sensors. In addition to the tactile arrays, force- and torque-sensing devices are also either commercially available for use by robotics systems or incorporated into some robotic systems. The most common of these are the wrist force/torque sensors and the finger force/torque sensors. In both such cases, strain-gauge-type transducers are usually used to measure the forces and torques applied at the robot end-effector. Actual force control algorithms for robots using wrist force sensors are available (36–38).

Vision systems are the most popular of noncontact sensors used in some robot systems. In addition to external sensing in robotics, vision systems have a number of other applications in industrial automation, including inspection, character recognition, and visual navigation. In an industrial robot, a vision system is usually used to identify and locate objects in the robot environment. The robot then performs vision-controlled manipulation of the objects. Commercially available robotic vision systems are most effective in two-dimensional scenes, require known or high-contrasting backgrounds, can only handle rigid and isolated or partially touching parts, are programmed in teach-driven mode, can handle only a limited number of objects, have limited processing times for part recognition, and lack interfaces to robot or manufacturing cell programming environments.

Commercially available vision systems are also relatively costly and therefore their use for industrial applications is limited. Vision systems have also been used for end-point visual sensing in data-driven environments to improve the robot accuracy. Commercial robot systems also exist with vision-controlled seam-tracking capability for arc-welding applications (see eg 39).

In addition to vision systems, other types of optical sensors have been used as external sensors in industrial robots. One example is the use of linear arrays of light transmitters and receivers in the end-effector fingers. It has been shown (40) that a small number of sensors arranged on a robot in this way can provide a substantial amount of shape information about the object being manipulated.

In using external sensors, the user usually has to provide the sensors, the sensory processing, and the motion-control algorithms for manipulation of objects based on the sensory data. Although many types of external sensors are commercially available, in most existing industrial robots, the user does not have the capability to input trajectory points directly from an external source to the robot controller. This lack of data communication interfaces limits the use of external sensors to those built into the robot directly by the manufacturer. Many manufacturers, for example, provide integrated vision systems for their robots.

Most commercially available robots are designed to be used in a stand-alone mode rather than as a part of an integrated system with a central processing unit. For this reason, robots support only the simplest data communication interfaces, such as RS 232. Standardization is also lacking in the data communication interfaces between robot controllers and their user programming systems. However, the controllers for some commercially available robots support parallel operations involving the robot and other user-defined devices, although these controllers do not support interfaces to other computers or local area networks.

Human-Machine Interfaces

The last component group of a robotic system is the human-machine interfaces of the robot. Such interfaces are necessary to permit effective human programming, implementation, monitoring, and control of the robot. The human-machine interfaces of a robot, therefore, influence its communication function insofar as it relates to the robot user.

There are several existing types of user interfaces for programming robots. Some robots are programmed by leading the robot through the task. Others are equipped with a teach pendant or a joystick for their programming. In these cases, robot application programs are developed through a teach playback loop. Some robots are equipped with a high-level programming language, in which case robotic application programs are developed through an edit-compile-play loop. More modern interactive robot programming environments have also been developed (41,42) where programming and debugging of robot applications are less tedious because of the interactive nature of the programming system. CAD-based robot programming systems (see eg Ref. 43–45) also exist. Most such systems, however, have only been used for off-line robot application planning and simulation and have not been interfaced to actual robot hardware.

A major problem today is the variety of programming languages offered for robotic application development. Different manufacturers offer their own version of a high-level programming language (AML from International Business Machines, KAREL from GMF, and VAL/II from Unimation). Most of these languages are developed from the programmer's aspect, rather than from the user's or manufacturing engineer's point of view. As a result, such languages are frequently more difficult to use than is necessary to accomplish the robot application implementation.

Use of the voice to guide a robot through a sequence of movements necessary for performing a task provides a totally different approach to robot programming. Such methods have been investigated for applications involving robotic aids for the handicapped and in space applications. The problem with such systems is that existing speech recognition systems are either speaker-dependent or constrained to a severely limited vocabulary of a few dozen words.

In summary, the most common commercial offerings of industrial robots have the following functional characteristics and limitations.

- Low-precision manipulation capability with high sensitivity to load disturbances.
- Very limited sensor integration
- Limited data and control communication capabilities
- Simple control actions insensitive to parameter and environmental changes
- Very limited user-independent decision-making capability.

Most robots are designed to work in regular factory environments. Several offerings also exist for up to class 10 clean room operations used in semiconductor manufacturing. The operational speeds of these systems during the clean room operations, however, are restricted to no more than 70% of their rated speeds to ensure compatibility with clean room operation. Standardized procedures and tests for recertification of clean room robots after maintenance are also lacking. In general, there is a lack of experience or standardized qualification test procedures (46) for all types of robots. The performance data specified for a robot by a manufacturer in many cases is based on design specifications rather than on test data. Realistic reliability data on most commercially available robots is also lacking. A typical availability factor (47) for most commercial systems is in excess of 97%. Safety mats, light curtains, interlocked fences, or system enclosures are currently used to ensure safety of personnel and other machines working in the general vicinity of the robot; safety standards for robots have yet to be developed.

It should also be pointed out that present robot technology includes a broad spectrum of industrial robot offerings ranging in cost from less than $10,000 to more than $100,000.

MARKET TRENDS AND APPLICATIONS

In studying the influence of the market characteristics on the next generation of industrial robots, it is important to study not only the present trends but also the expected changes in the market trends over the next decade. Robotics is a relatively new technology and its market trends are expected to change drastically due to the increase in the experience base in robotics and more widespread acceptance of robots in industry.

At present, most industrial applications of robots are limited to either simple repetitive tasks or to applications which, to a great extent, are insensitive to part or process tolerances, require low precision and little or no interaction with other equipment. This is reflected in the high percentage of U.S. robot sales for simple applications involving machine tending, material handling, spot and arc welding, and spray painting (see Fig. 2). Other, more sophisticated applications, such as electronic assembly, high-precision processing and inspection have not yet captured a large share of the robot market because of the limited capabilities of present robot offerings. A Delphi study (48), however, indicates that robot sales for these applications will grow sharply over the next decade; it is expected that the fastest growing application for industrial robots will involve assembly operations for the electronic industry, which must compete with foreign manufacturers who enjoy lower labor costs. Sales of industrial robots for other applications, such as high-precision processing and inspection, are also expected to grow over the next decade (see also FUTURISM AND ROBOTICS).

Understanding robotic market trends by application is important in assessing the demands on the capabilities and performance of the next generation of robotic systems. The Delphi study (48) provides a comprehensive assessment and forecast of robot market trends and technology. For example, this study indicates that although market share of the more sophisticated robot applications will grow, material handling will remain the biggest sector of the market. In addition, as the experience base in robotics grows, many industries will increase their utilization of robot technology. Understanding robot market demands by industry is important in assessing the characteristics of future robot technology because it is influenced by development efforts aimed at responding to such demands.

At present, the automotive industry is the leading customer for industrial robots. The Delphi study forecasts that although absolute automotive demand is expected to remain the same over the next decade, the relative share of other industries in the robot market is expected to increase significantly. Figure 3 provides a comparative summary of the expected robot market growth in different industries, based on the data in the Delphi study (48). This figure clearly indicates the expected significant increase of the robot market share of the electronic industry by the end of the decade. Other significant increases are indicated for the machinery-manufacturing, aerospace, and non-metal commodity industries.

In addition to the manufacturing-related industries cited above, significant future applications of robot technology in some service and medical industries are expected. In the service industries robots are expected to be applied with increasing frequency in places or situations which are inaccessible or hazardous to humans. Such applications include maintenance of nuclear reactors, operations in space, mining operations, ocean floor operations, accident missions, and combat support. In medicine the application of robotic technology is expected to grow in human augmentation in performing delicate surgical tasks, in robotics aids for the handicapped, and in augmentation of human extremities by prosthetics and orthotics.

NEXT GENERATION OF ROBOT TECHNOLOGY

The characteristics of the next generation of industrial robots can be extrapolated from the limitations in the present technology, market trends, and expected advances in component technologies. Improvements in all of the five basic functions of manipulation, sensing, communication, control, and decision making are expected in future robot technology. Advances in all component groups of robot technology will influence such improvements.

The next generation of mechanical manipulators is expected to be modular, composed of substructures (arms, wrists, micromanipulators, etc) that can be easily assembled into a variety of robot configurations. In addition, future robotic systems are expected to incorporate parallel manipulator architectures or multi-arm manipulator systems, with coordinated movements. The use of cooperative multi-arm systems will reduce the cycle time necessary to perform a task, which is important in many manufacturing or repair applications, such as nuclear reactor maintenance.

The precision of available manipulators is also expected to be improved substantially, enabling the next generation of

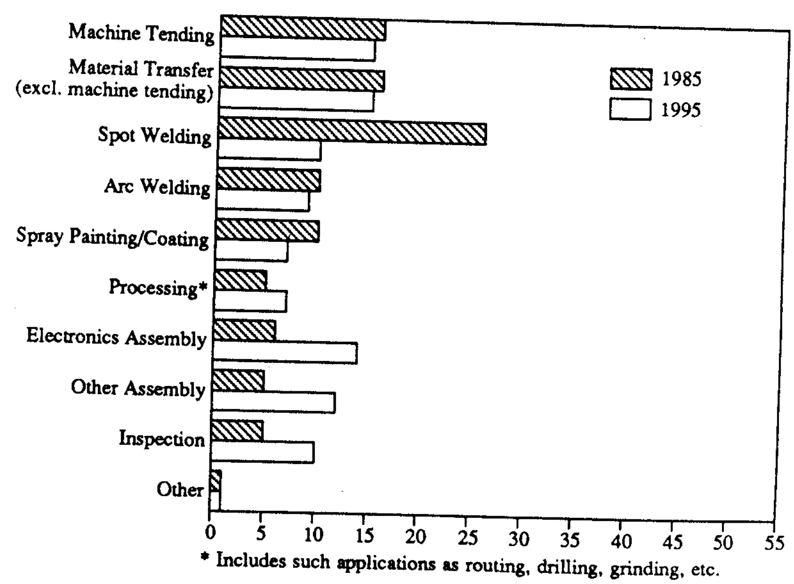

Figure 2. Percentage distribution of robot sales in the U.S., by robot application (48). Courtesy of the University of Michigan and the Society of Manufacturing Engineers.

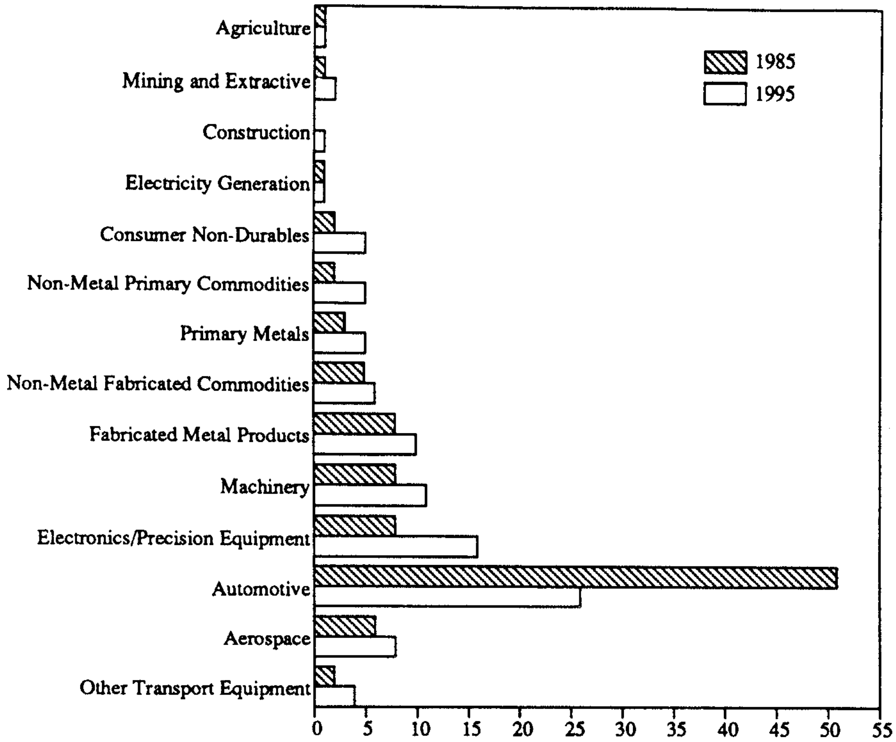

Figure 3. Percentage distribution of robot sales in the U.S., by industry (48). Courtesy of the University of Michigan and the Society of Manufacturing Engineers.

robotic systems to be fully utilized in electronic assembly, inspection, and precision machining applications. Current semiconductor manufacturing processes require robotic system precision on the order of 9.8×10^{-6} in. (± 0.00025 mm). Since data-driven robotic systems are expected to become more widely used in such applications, robot-positioning accuracies of the same order are needed. Such accuracy requirements are very ambitious and seem to be beyond the capability expected in the next generation of robotic systems unless a revolutionary technology is introduced. Another approach to such critical accuracy requirements may be implementation of fine positioning devices (micromanipulators) at the end of the manipulator, or the incorporation of vision systems for end-point sensing. In electronic subassembly and box plant applications, however, data-driven robotic systems with less stringent accuracies in the range of 9.8×10^{-4} to 3.9×10^{-4} in. (± 0.025 mm to ± 0.01 mm) are sufficient. The next generation of robotic systems is, therefore, expected to include a wider variety of offerings within this accuracy range. Electronic industry also requires robotic systems of up to Class 1 for clean room applications. In the final analysis, the cost of mass-producing Class 1 robot systems may prove to be excessive. In most applications, however, the entire robot system does not need to be ultraclean (Class 1); only the immediate volume in which the value add operation is being performed must be. This means that developing and using Class 1 end-effectors and/or wrists may be sufficient in performing many ultraclean operations. This will keep the cost of the entire robot system within a more reasonable limit.

Inspection applications put demands on the precision of robotic systems similar to those of the electronic industry. The requirements of precision machining applications, moreover, extend not only to the precision of the robot but also to its load-carrying capacity at the rated precision. Manipulators are needed that would have low deflection under load or high end-point stiffness. Expected advances in manipulator geometry and structure will improve the vibration characteristics and end-point stiffness of the commercial robot offerings. In addition, generic joint- or tool-level auxiliary mechanisms (see eg Refs. 47,48), such as tool guides, that would improve the end-point stiffness of a robot are expected to become commercially available.

The next generation of end-effectors will have features including quick-change capability, modularity, dexterity, robot/tooling protection devices, and incorporation of sensors. The general requirement to interact with a wide range of parts suggests the need for a universal end-effector. Although the potential exists to eventually develop an economical design for a robot-integrated universal gripper, the next generation of end-effector technology will emphasize interchangeability and sensory features.

The joint servo-drive systems for the next generation of robotic systems are also going to benefit from advances in component technologies. Usage of direct drive technology is expected to become more widespread among commercial robot offerings. Robot controllers should also become more generic and modular, and provide not only position control but also force or hybrid position/force control. The demand to use robots in applications requiring high precision with low sensitivity to load disturbances will push the robot controllers to use adaptive and robust control techniques. In addition, due to expanded use of external sensors, robot controllers must provide for real-time control of the robot joint motions and they must also process data coming from multiple sensors and make motion control decisions. Such processing demands are expected to result in future robots have distributed and multitasking control functions. Advances in VLSI technology are expected to improve the computational capabilities of robot motion control software, thereby improving the task control capabilities of the next generation robotic systems.

In the area of robot external interfaces, improvements in both external sensors and data communication capabilities are expected in the next generation of robotic systems.

Tactile sensing pads that are small enough and have the proper response time and sensitivity to be used at the fingertips of robot hands will become commercially available. Data from such sensors can enhance the functionality of mechanical hands in grasping and precisely manipulating objects. Slip-sensing technology is also expected to become widely available and used in robotic systems designed for handling hazardous materials. Integrated force-sensing devices should also become more widely available.

In the next generation of robotic systems, vision sensor-robot hardware/software integration will be achieved at economical costs. Recent advances in image-processing algorithms, serial processors, programming languages, and nonrelaxation architectures are expected to bring about commercial robot vision systems with the following characteristics:

Image-processing time of less than 0.5 s
High resolution
Large identification capacity
Multiple camera support
User-friendly and robot-integrated programming language
Insensitivity to scene lighting and image contrasts
Handling of overlapping or partially overlapping objects

Such systems are also expected to have simple and accurate calibration set-ups. Color vision should become commercially and more widely available.

The data communication interfaces for the next generation of robot systems are expected to support not only the external sensors and actuators but also host or cell computers and local area networks. It is also expected that standardized data communication protocols and interfaces will become available for robot controllers and their user programming systems. Such interfaces provide the user with the option of controlling the motion of the robot with an externally generated motion control program rather than with what is provided by the manufacturer in the robot controller. This capability enhances the use of robots in manufacturing cells under the control of a host computer or the use of generalized planning or off-line programming software for programming the robot.

In the area of human-machine interfaces, the last component group of robotic technology, significant improvements are expected in the next generation robotic systems. The complexity of human interactions required for programming and monitoring robotic applications will be significantly reduced. Industrial demands to use data-driven automation together with advances in CAD/CAM technology, robot programming languages, and artifical intelligence are expected to produce robot-integrated CAD-based off-line programming systems, task-level programming languages, and expert-system-type task-planning consultants.

Improvements in computer-based discrete work voice-recognition systems are expected to result in voice-commanded manipulators under direct human voice control. Such systems are expected to have a larger motion control vocabulary base than the existing voice generation systems and become commercially available in the form of an integrated robotic system.

From a system point of view, the next generation of robotic systems are expected to be more reliable, cost less, and incorporate integrated maintenance and safety factors as well as training programs. Performance-testing techniques are also expected to become more standardized and widely available.

SUMMARY

A forecast of robotic technology based on expected innovations in present component technologies and evaluation of future market trends indicates that the next generation of robotic systems will have the following functional characteristics:

- Improved manipulation performance in terms of precision, load capacity, and stiffness
- Integrated sensor and control functions with sensor-influenced behavior modifications
- Well-orchestrated data and control communication with other devices, computers, users, and local area networks
- Improved, more robust, and adaptive control actions
- Interactive, sensor-based, and expert-type planning and decision-making ability

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