Robotics: challenges to present-day technology

James S. Albus

Robots must be produced in great numbers with more advanced capabilities, and we must lose our fear that they are taking over our jobs

Robots have received a great deal of publicity lately. The enormous influx of foreign cars manufactured in part by robots has aroused the awareness of the press and many politicians to the fact that robots can have a profound effect on industrial productivity. Many people today believe that the robot revolution is well under way, that factories are full of armies of these highly intelligent "steel-collar workers," and that human workers are being displaced in droves. The facts are quite different.

First of all, there are only about 6000 robots installed in the entire country. So at least for the present, robots are having almost no effect on overall productivity. Today, robots are being produced at the rate of about 1500 per year. Predictions are that this will grow to 20 000 to 60 000 robots per year by 1990. At that rate, the U.S. will be lucky to have a million robots in operation before the year 2000.

Second, the great majority of robots today are quite primitive, with no capacity to see, feel, or respond to their environment in any significant way. In their simplest form, they are nothing more than mechanical devices programmed to perform some useful act of manipulation or locomotion under automatic control. An industrial robot is a device that can be programmed to move some gripper, or tool, through space to accomplish a useful industrial task.

However, the majority of industrial tasks are beyond the capacities of present-day robot technology. Most tasks are too complex and unstructured, involve too many uncertainties, or require too much ability to see, feel, and adapt to changing circumstances.

Third, workers in the U.S. are not losing their jobs because of a few thousand robots. Auto workers are suffering unemployment more because of robots in Japan than because of robots in Detroit. If we continue our present low productivity rate, we cannot help but face even greater unemployment.

So before robots can significantly impact productivity, there must be a drastic change in the production rate of robots in this country. Furthermore, these robots must be so designed that they can be used in hundreds of thousands and even millions of applications. This will not be possible until a large number of technical problems are solved and social perceptions are changed [see box].

Positioning accuracy

First of all, robot positioning accuracy needs to be improved. Although the repeatability of most robots is on the order of 0.050-inch over its working volume (and in some cases as good as 0.005-inch), the absolute positioning accuracy may be off as much as 0.250-inch, or even 0.500-inch in some regions of the reach envelope. Thus, it is not possible to program a robot to go to an arbitrary mathematically defined point in a coordinate space and have any assurance that it will come closer than half an inch. This creates major problems in programming a robot from a computer terminal, or in transferring programs from one robot to another. Each robot must be taught its program separately by leading it point by point through its job, a tedious and costly task.

Presumably, this accuracy problem could be solved through closer robot manufacturing tolerances, although not without cost. Alternatively, calibration procedures might allow each robot to offset its off-line program points (i.e., programmed from a computer terminal) to compensate for its mechanical inaccuracies.

No efficient methods of robot calibration have yet been developed, however, and robot control software is not presently designed to use calibration tables for improving absolute positioning accuracy. Until this problem is solved, robot assembly in the small-batch environment will be uneconomical. Teaching a robot every point in the trajectory of a complex assembly task is a time-consuming job that may take many times longer than would be required to perfom the same task by hand. Thus, using a robot for small-lot batch assembly cannot be economical until software can be efficiently produced by off-line programming.

Dynamic performance

Dynamic performance is another area that must be improved. Present-day robots are too slow and clumsy to effectively compete with human labor in assembly. Two possible exceptions to this are in arc welding where speed is governed by the welding process itself, and spot welding where the task corresponds to moving a heavy welding gun through a simple string of points in space—a procedure that the robot is particularly adept at executing [see photo].

If robots are to perform other types of assembly and construction tasks, they must be able to execute much more complex routines with much greater dexterity and speed than they are now capable of. Control systems need to be alternately stiff and compliant along different axes in space (which do not generally coincide with joint coordinates). This requires much more sophisticated cross-coupled servo control computations than are presently employed.

Furthermore, robot structures are typically quite massive and unwieldy. Most robots can lift only about one-tenth of their own weight. Many cannot even do that. New mechanical designs using lightweight materials such as carbon filament epoxies and hollow tubular construction are needed. Advanced control systems that can take advantagve of such lightweight structures and high speeds will be a major research project.

Much also remains to be done in gripper design. Typically, robot hands consist of pinch-jaw grippers with only one degree of freedom—open and shut. Contrast this with the human hand which has five fingers, each with four degrees of freedom.

No robot has come close to duplicating the dexterity of the human hand, and it is not likely that one will in this century. Certainly, dexterous hands with jointed fingers for industrial robots are a long way in the future. The problem is not so much in building such a mechanical structure, but in controlling it. No one has any idea how to design control algorithms to make use of such complexity and very little research is being done in this area.

Sensors

Robot sensors of many different types must be developed. Robots must become able to see, feel, and sense the position of objects in a number of different ways. Processing of visual data must become faster and be able to determine 3-D shapes and relationships. Robot grippers must become able to feel the presence of objects and sense the forces developed on those objects.

Proximity sensors are needed on robot fingertips to enable the robot to measure the final few millimeters before contacting objects. Longer range proximity sensors are needed on the robot arm to avoid colliding with unexpected obstacles. Force and touch sensors are needed to detect and measure contact forces.

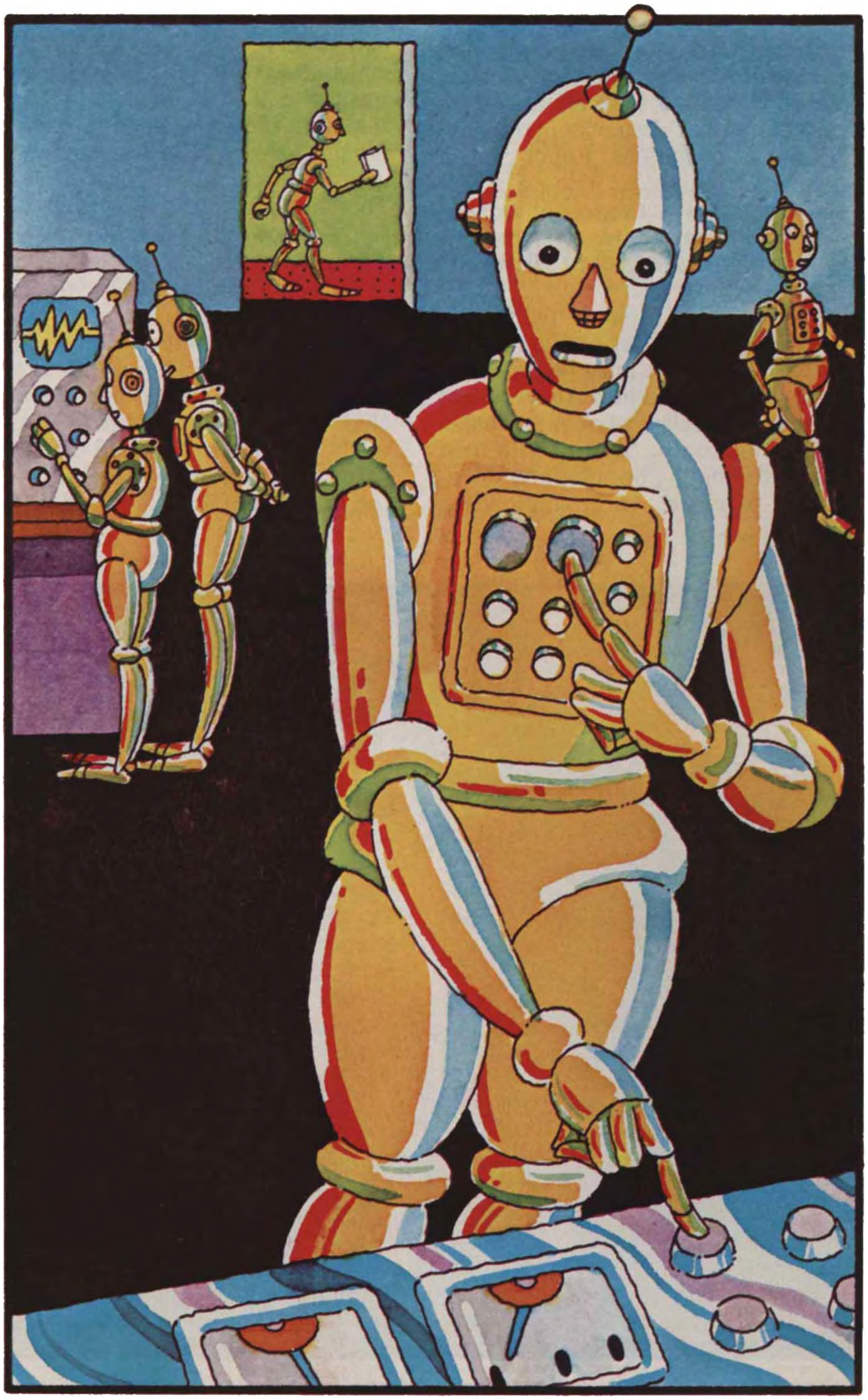
A variety of acoustic, electromagnetic, optical, x-ray, and particle detectors are needed to sense the presence of various materials such as metals, ferromagnetics, plastics, fluids, and limp goods, and to detect various types of flaws in parts and assemblies. Both the sensing devices and the software for analyzing sensory data represent research and development problems of enormous magnitude.

Robot sensing is an area where there is much research activity. Robot vision is by far the most popular research topic, and also probably the most difficult. A computer must treat a visual image as an array of brightness dots called picture elements, or pixels. A typical scene may consist of from 16 thousand to over a million pixels.

Interpretation of such a large volume of data is an enormous task even for a high-speed computer. It often takes many seconds to several minutes to analyze a single picture by computer. This is far too slow for the robot to respond in a timely fashion to what it sees.

Various tricks are used to speed response time. One is to illuminate the scene so that the objects appear as black and white silhouettes. Another is to assure that no two objects of interest touch or overlap. However,

Art Sudduth



even under such artificial circumstances robot vision is a very complex problem. Such techniques obviously limit the use of robot vision to a few select applications.

Other robot sensory inputs such as touch and force appear to be simpler in principle, but much less work has been done in these areas.

Control systems

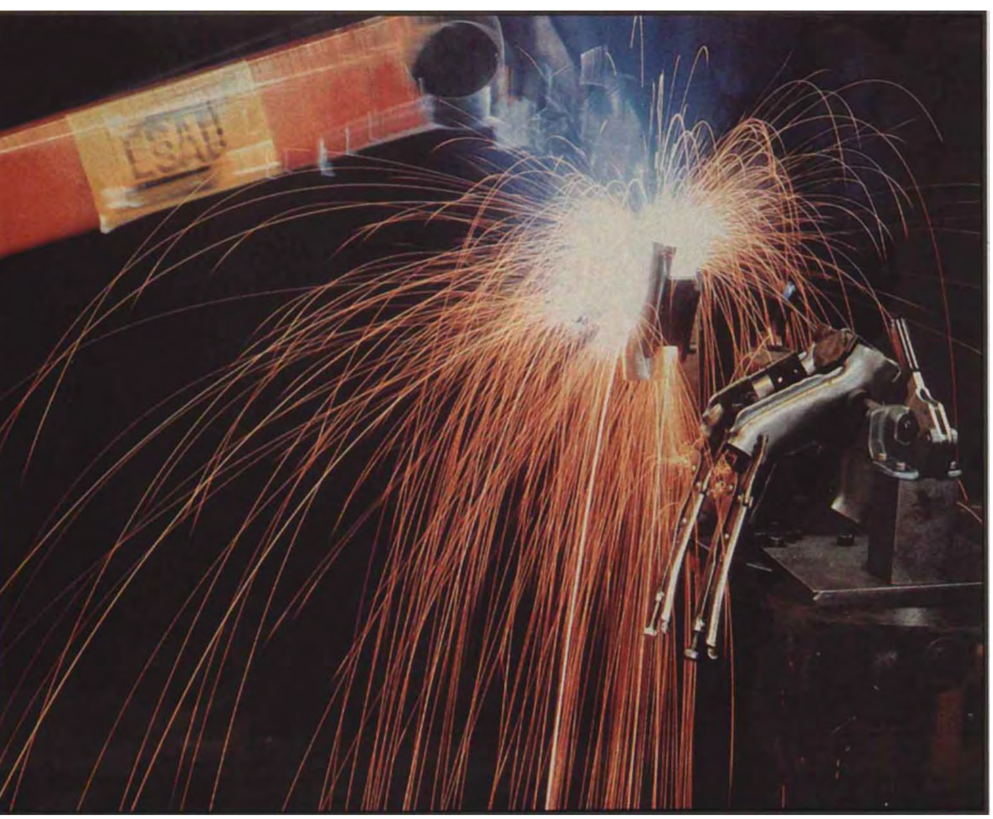
Control systems are needed that can take advantage of sophisticated sensory data from a large number of different types of sensors simultaneously. Present control systems are severely limited in their ability to modify a robot's behavior in response to sensed conditions. Robot control systems need to be able to accept feedback data at a variety of levels of abstraction and have control loops with a variety of loop delays and predictive intervals.

Sensory data used in tight servo loops for high-speed or high-precision motions must be processed and introduced into the control system with delays of no more than a few milliseconds. Sensory data used for detecting the position and orientation of objects to be approached must be available within hundreds of milliseconds. Sensory data needed for recognizing the identity of objects or the relationship between groups of objects can take seconds. Control systems that are properly organized in a hierarchical fashion so that they can accommodate a variety of sensory delays of this type are not available on any commercial robot.

Internal computer models

Robot control systems need to have much more sophisticated internal models of the environment in which they work. Future robot control systems will have data bases similar to those generated by computer-aided-design (CAD) systems, and used for computer graphics displays. These can describe the 3-D relationships of both the workplace and the workpieces.

Such data bases are needed to generate expectations as to what parts should look like to the vision system, or what they should feel like to the touch sensors, or where hidden or occluded features are located. Eventually, such internal models might be used in the automatic generation of robot software; for example, describing how a finished assembly should look, or even how each stage of an assembly or construction task should appear in sequence.



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Today, a large number of robots are highly productive in spot and arc welding, where the environment is hot, dirty, and unpleasant. A human welder can keep a torch on 30 percent of the time, compared to 90 percent for a robot welder. However, if this type of productivity is to be seen in other areas, advances in robot technology are essential.

Improved software development

Techniques for developing robot software must be vastly improved. Programming-by-teaching is impractical for small-lot production, especially for complex tasks where sensory interaction is involved. Shop-floor personnel unskilled in computers must be able to instruct robots in what to do and what to look for in making sensory decisions. Eventually, it will be necessary to have a whole range of programming languages and debugging tools at each level of the sensory-control hierarchy.

The development of compilers and interpreters and other software development tools, as well as techniques for making use of knowledge of the environment derived from a number of different sensors and CAD data bases, are research topics that will require hundreds of person-years of highly skilled systems software talent.

Interface standards

Interfaces need to be defined in some standardized way, so that large numbers of robots, machine tools, sensors, and control computers can be connected together in integrated systems. Trends in the fields of computer-aided manufacturing (CAM) are toward distributed computing systems wherein a large number of computers, robots, and machine tools interact and cooperate as an integrated system. This creates great software problems.

Particularly in the case where sensors are used to detect variations in the environment and to modify the control output to compensate for those variations, the software can become extremely difficult to write and virtually impossible to debug. In order for such systems to work at all, it is necessary to partition the control problem into modular components and then develop interface standards by which the various system components can communicate with each other.

It is often felt that standards are an inhibiting influence on a newly developing field—that they impede innovation and stifle competition. In fact, just the opposite is true. Well-chosen interface standards promote market competition, technology development, and technology trans-

Living with robots

Beyond acquiring the necessary funding and solving the technical problems discussed in this article, the other most important problem that must be solved is the perception humans have of robots and of the role they will play in society. Many people question the desirability of rapid, massive deployment of robot technology, fearing that such action will cause great human unemployment, since productivity improvement by its very nature reduces the amount of human labor needed to produce a given product. However, widespread unemployment is not the inevitable result of rapid productivity growth. More work can always be created. All that is needed is a way to meet the payroll. Markets are not saturated. The purchasing power of consumers can always be increased at the same rate that more products flow out of the robot factories.

Nevertheless, the average person is unconvinced that advanced automation would necessarily increase spending power. The question is, If the robots have most of the jobs, how will average people get their income? For most people to be convinced that robots will bring more benefits than problems they must be shown that a variety of alternative income-producing occupations can be created to fill the void.

Perhaps the most obvious source of new jobs is in the industries that must be created in order to convert to a robot-based economy. Certainly if robots are to be manufactured in large enough quantities to make a significant impact on the existing industrial system, entirely new robot manufacturing, sales, and service industries will emerge and millions of exciting new jobs will be created. A typical industrial robot costs from $30 000 to $80 000 and sometimes more by the time it is installed and operating. This means that every robot installed creates from two to four person-years of work somewhere in the economy. The robot market is presently growing at about 35 percent per year, which means it doubles about every three years. As long as this growth rate continues, robot production should add jobs to the economy about as fast as robot installation takes them away.

It will be many years before robots can design, manufacture, market, install, program, and repair themselves with little or no human intervention. In the meantime, the manufacture and servicing of robots will produce an enormous demand for mechanical engineers, technicians, computer programmers, electronic designers, and robot installation and repair persons. New robot companies will require secretaries, sales people, accountants, and business managers. It seems likely that the robot industry will eventually employ at least as many people as the computer and automobile industries do.

In general, industries that use the most efficient production techniques grow, prosper, and hire more workers. Workers displaced by automation are simply transferred into new growth areas or retrained for different occupations. It is in the industries that fall behind in productivity that job layoffs are prevalent. Inefficient industries lose market share to competitors, shrink, and eventually die. Thus, the biggest threat to jobs is not in industries that adopt the latest robot technology, but in those that do not.

The real question is whether we can evolve a society in which robots will complement, not compete with, humans for their livelihood. To protect the human worker's livelihood in the coming decades there are several steps that can and should be taken.

First, we must provide retraining for workers displaced by robots in new and better occupations. Second, we can decrease the workweek. It is not written in stone that humans must work 40 hours a week. As robots take over more and more work, humans can improve their work environment and decrease their work periods to 30, 20, or even 10 hours a week. Education and leisure activities can be increased virtually without limit. Eventually, all "work" could be voluntary.

Employee stock ownership plans, individual robot-owner entrepreneurs, and even semipublic mutual fund ownership plans might be developed in the future. If everyone could own the equivalent of one or two robots, everyone would be financially independent, regardless of whether they were employed or not.

Finally, we must recognize that it is premature to worry about insufficient work to go around. Much work still needs to be done in eliminating poverty, hunger, and disease throughout the world. We need to develop renewable energy resources, clean up the environment, rebuild our cities, exploit the oceans, explore the planets, and colonize outer space. The new age of robotics will open many new possibilities. What we humans do in the future is limited only by our imagination to see the opportunities and our courage to act on our beliefs.

—*J.S.A.*

fer. They make it possible for many different manufacturers to produce various components of modular systems.

Standard interfaces ensure that multivendor systems will fit together and operate correctly. Individual modules can be optimized and upgraded without making the entire system obsolete. Interface standards also make it possible for automation to be introduced incrementally—one module at a time. Systems can be made upward-compatible and automated piecewise. Thus, users can test the automation waters gradually, without a large initial capital barrier.

Robot mobility

Many potential robot applications require robot mobility. Most robots today are bolted to the floor or to a tabletop. Small robots can reach only one or two feet, while larger ones can grasp objects nine or 10 feet away. But many applications need robots that can maneuver over much larger distances. For example, a robot used to load a machine tool typically spends most of its time waiting for the machine tool to finish its operations. Sometimes a single robot can be positioned between two or more machine tools so that it can be more fully utilized. However, this leads to severe crowding of the work environment and in many cases is simply not practical.

There are a few applications in which robots have been mounted on rails so that they can shuttle between several machines. Unfortunately, to date, this has proven too expensive and cumbersome for wide-scale use.

For the most part, these eight technical problem areas encompass profound scientific issues and engineering problems that will require much more research and development. It may be possible to improve the mechanical accuracy of robots, and to improve servo performance with little more than careful engineering. But much more fundamental research and development will be required before the sensor, control, internal modeling, software generation, systems interface, and mobility problems are solved [see page 41].

Given enough time and resources, robotics will enventally become a significant factor in increasing productivity in industrial production.

About the author

James S. Albus is presently acting chief of the Industrial Systems Division for the National Bureau of Standards. He is the author of numerous articles on robotics and has received the Dept. of Commerce Silver Medal for Industrial Research, IR-100, award. □

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