Potential Applications of Robotics in Transportation Engineering

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Deficiencies in transportation facilities must be addressed urgently. The adoption of new technologies into the transportation sector is necessary to the productive and economic rehabilitation, repair, and maintenance of the infrastructure of existing transportation systems. The continuous need for construction and rehabilitation and repair and maintenance of transportation network systems, specifically under uncontrolled environments, is an issue addressed in conjunction with robotic applications. The nature of robot tasks is discussed in this paper to provide general knowledge about this technology. Also discussed are robot attributes and the manipulation of robots for tasks such as welding and painting of highway bridge components. Current research in other robot applications such as sealing, grinding, sandblasting, inspection of concrete pavements, handling of precast concrete beams, fabrication of steel and reinforcing bars, excavation, tunneling, roadside management, hazardous material handling, railway track maintenance, nuclear plant clean-up, and the use of robots in harsh environments are also described. Although the United States currently has a lead in artificial intelligence, related computer technologies, and some areas of robotics, large-scale field applications of robots is the biggest challenge to this infant technology. There is a great need for a comprehensive, unified robotic research information system for the dissemination of information on robotics in transportation.

In the United States today, there are almost 4 million mi of streets and highways. Some of these were built long ago by using old, conventional techniques and materials. Many of them are already deteriorated and need rehabilitation and replacement. Deficiencies have been developing in this transportation system at a rate faster than funds have become available to keep it serviceable. For example, there are approximately 575,000 bridges in the street and highway system, of which more than 44 percent are considered deficient in one way or another. Similar problems exist for the railroad system, comprising 166,000 mi of mainline roads and more than 100,000 mi of other rail lines, all with track structure and bridges requiring maintenance and rehabilitation (*1*). These observations show that current and near-future research trends in the transportation sector will focus on innovative strategies such as robotics for the improvement of infrastructure facilities.

Transportation projects have always involved construction operations that are highly equipment intensive. Although some of these operations have made use of automation technology in varying degrees, developments in robotic applications, such as in Japan, should prompt more research in the United States in advanced technologies like robotics and artificial intelligence. These technological innovations have definite potential in bringing about dramatic increases in the productivity and quality of operations.

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In the foreseeable future, most of the traditional civil engineering projects can be expected to evolve and adapt to changing market conditions. Even in established disciplines such as transportation, water supply, waste treatment, and geotechnical engineering, pressures from urban growth and resource depletion will (a) force technological advancement toward tackling increasingly constrained conditions in subway and sewer tunnels, (b) minimize disruption in highway and utility structures, and (c) maximize the flexibility and utility of buildings. Advances in materials and design concepts, coupled with the need to reduce the risk of failure associated with natural calamities such as earthquakes, floods, hurricanes, and fires, will continue to mandate advances in structural engineering. This paper focuses on the issues involved in robot applications in transportation engineering; the nature of robot tasks and attributes of robots; the use of robots in construction inspection, tunneling operations, roadside management, the handling of hazardous materials, railway track maintenance, and space applications; and the use of expert systems in robot task planning. The main theme of the paper is to recognize the tremendous future in advanced technologies for civil engineering among which robotics is a challenging yet highly beneficial technology.

The use of robotics in civil engineering currently is still in its infancy. The Japanese have successfully introduced a few robots in the building environment. These robots have the potential to shrink personnel requirements, boost productivity, and relieve human workers of hazardous and repetitive work (*2*). Recently, the 5th International Symposium on Robotics in Construction in Tokyo, Japan, emphasized that research has been forthcoming in the field of construction robotics. Several successful robotic applications have been illustrated to demonstrate the feasibility of this technology in the domain of construction. Similar robot applications can be introduced into transportation construction and infrastructure rehabilitation operations as discussed later in this paper.

NEED FOR APPLICATION OF ROBOTICS IN TRANSPORTATION ENGINEERING

Transportation engineering is now poised to adopt advanced technologies and innovative strategies to improve productivity and performance. A recent workshop sponsored by the National Science Foundation to examine the state of the art and research opportunities in transportation showed that the ultimate objective of research in the areas of transportation facilities is to develop technological innovations that will result in substantial improvements in the quality of transportation facilities, including productivity and performance (*3*). Fundamental research on transportation facilities has also been outlined for repair, rehabilitation, and maintenance with the use of robotics and other automated systems (*4*). The type of work commonly called "3R" (resurfacing, restoration, and rehabilitation) as applied to highways (*5*) has the greatest benefit in robot applications, apart from areas such as assessment of facilities conditions, use of new materials in highway components, and vehicular navigation, control, and location (*6*).

Current technologies and practices to rehabilitate existing facilities have been derived largely from those of new construction. However, the market for these two types of activity and the types of work involved are different in some important respects. Whereas new construction comprises a mix of project sizes ranging from multibillion-dollar megaprojects to small bridges, rehabilitation is much more consistently a small-scale proposition—patching, replacing, strengthening, sealing, painting, lubricating, and so on. Therefore, the natural occurrence of economies of scale, the incentives toward mechanization and use of improved material and techniques, and the corresponding development of larger, efficient organizations have not yet taken place in rehabilitation (*5*).

If possible, rehabilitation efforts must take place without closing down transportation facilities. Furthermore, work space is typically confined and may often be inaccessible or invisible to work crews using standard construction technology (*5*). If work has to take place outside of peak hours, issues such as overtime compensation for workers, additional lighting facilities during dark hours, and scheduling of activities need to be addressed. These factors have not been reflected strongly so far in productivity and performance analyses in the transportation sector because the volume of rehabilitation work has been small on an overall basis. But the need for new construction shows a relative decline compared with the need for rehabilitation work. Highway needs formed nearly 86 percent of estimated infrastructure needs of the transportation sector (*6*). For example, highway needs studies prepared biennially by the Department of Transportation for the period 1975–1981 show that traffic (in vehicle miles traveled) grew at an annual rate of 2 percent during that time, with higher-than-average growth occurring on the interstate system. In that same interval, the interstate system, which carries a disproportionate share of the traffic, exhibited a decline in pavement condition overall, despite the addition of new mileage to the inventory (*5*). This trend will continue for some time, and it will become necessary to introduce advanced technologies such as robotics to quicken the pace of efficient infrastructure improvements and new construction.

Several potential areas of application of automation are recognized in this paper. Varying degrees of automation can be introduced in equipment ranging from automated data acquisition techniques to cognitive robots, as discussed below. However, it is useful to introduce some of the characteristics of modern robots before undertaking a discussion of their applications in transportation engineering.

Nature of Robot Tasks

Robots are classified in general into three classes, based on the amount of human intervention necessary to control them. The first of these, called teleoperated robots, are fully dependent on human operators for planning, perception, and manipulation. The second of these, called programmed robots, perform predetermined, definite tasks by preprogrammed instructions. The third of these, called cognitive robots, are capable of sensing, modeling, planning, and acting, independent of human operators.

The Robotics Institute of America defines a robot as a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks. Although this definition is valid to a point in the factory, it excludes the high- and low-end capabilities of devices that are relevant in unstructured and uncontrolled environments and underemphasizes the importance of mobility and force that are essential in construction (*7*). Highway construction and rehabilitation operations take place in unstructured environments. Since robots working in such environments require varying degrees of human intervention, the possibility of introducing all three classes of robots and their hybrids has to be expected (*7*).

Attributes of Robots

The attributes of robots that are important from the civil engineering standpoint are their manipulation, effecting, control, sensing, and mobility operations (*8*).

Manipulation

Robots usually have an arm that can reach and grasp an object and move it from one location to another. This action is facilitated by a wrist. Examples of common manipulation systems are shown in Figure 1: (a) three axial translations in rectangular coordinates; (b) rotation and biaxial translation in cylindrical coordinates; (c) two axial rotation and translation in polar coordinates; (d) three axial rotation in revolute coordinates; and (e) anthropomorphic or articulated (*8*).

Effectors

Effectors are devices that enable the robot to do any particular task. In civil engineering applications, effectors can be used for grasping, jointing, welding, painting, and other similar tasks. These effectors are operated by the manipulators. Typical effectors are the welding gun, spray painting nozzle, bolt-tightening grippers, sealing and jointing devices, and grinding disc (*8*). The grippers are used for "pick-and-place operations" and are of different types, such as finger grippers, suction grippers (for flat and smooth objects), magnetic grippers (for metallic objects), and tube grippers (for hollow circular tubes) and are shown in Figure 2 (*8*).

Control

Robots are classified in six groups based on the level of control or intelligence (*9*) as

- M1: Manual control (teleoperation);
- M2A: Fixed sequence built into the robot mechanical system;
- M2B: Variable control, according to preprogrammed instructions;

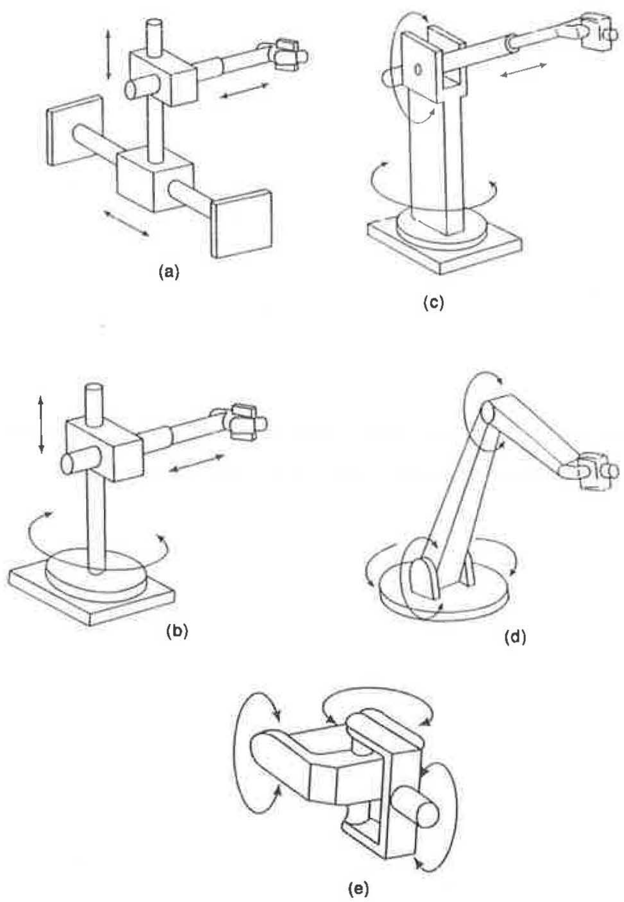

FIGURE 1 Typical configurations of industrial robots (a) rectangular, (b) cylindrical, (c) spherical, (d) jointed, (e) wrist (*8*).

- M3A: Playback, in which the control unit "learns" the desired sequence of arm movements when the arm end is guided by the operator on the path of its intended activity;
- M3B: Numerical control, using a computer language that the control understands; and
- M4: Artificial intelligence capabilities built into the robot, involving a process of learning from vision, contact, and hearing (7).

Sensors

Sensors are most useful in M4 type robots when the control unit can modify a manipulator's activity based on the information received from the environment during its performance. Various physical parameters such as sound, touch, and sight are converted into electronic signals that can be recognized and acted upon by the control unit of the robot (7).

Mobility

Robots being used in the manufacturing industry are mostly stationary. But robots for civil engineering purposes have to be mobile, since the places of operation are unstructured and are in different locations.

POTENTIAL APPLICATIONS OF ROBOTICS IN SPECIFIC AREAS OF TRANSPORTATION ENGINEERING

Robotization of transportation operations will be a challenging task. Unlike manufacturing environments that are structured, field operations in transportation involve unstructured and unpredictable environments. Consider the task of excavating a roadside trench for installing fiber optic cables. While excavating the upper layers of the soil, the system may encounter fine soil. But on digging deeper, the system may encounter hard rock pieces for which it is not prepared. This discovery would require a cognitive robot that can adjust its capabilities to changing situations. Coupled with uncertainties, robots have to be sensitive to other factors, such as varying temperature conditions at the site, range, and magnetic fields.

Robots operating under field conditions should be able to tolerate extreme conditions of roughness of terrain. To perform successfully a robot built for field operations should be able to survive in field conditions. So, future robots for transportation should be capable of moving over and around obstacles and also of climbing grades.

In transportation, numerous application areas exist and are outlined below.

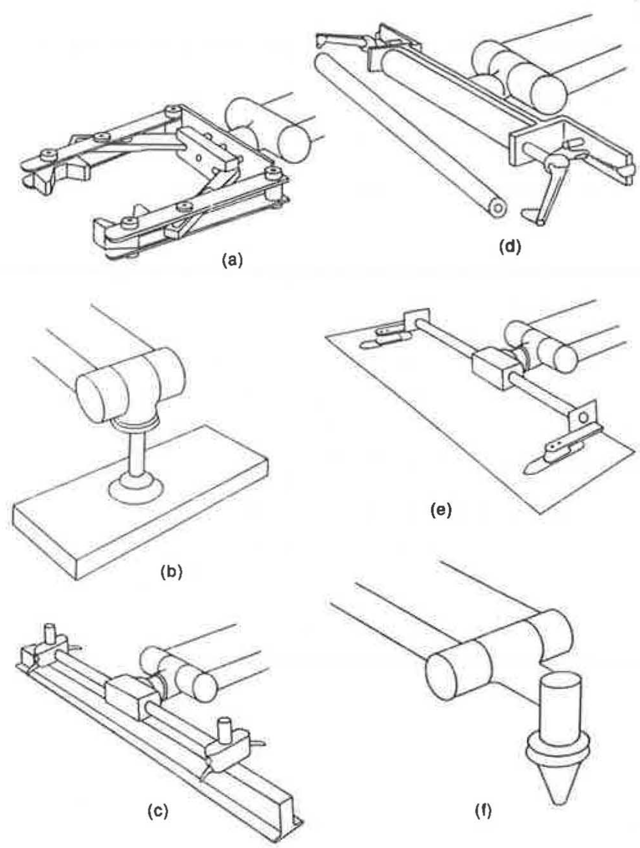

FIGURE 2 Robot Effectors (a) finger gripper, (b) vacuum gripper, (c) magnetic gripper, (d) tube gripper, (e) magnetic gripper, (f) grinder (*8*).

Steel Bridge Construction and Maintenance

Welding of Bridge Components

Robots routinely have been used in manufacturing plants for accurate welding of objects, with a good degree of success. Robots similarly could be used for welding purposes during steel bridge construction. Using one such robot developed in Japan, girders are manufactured by profile cutting of plate steel to the desired contours and then welding the cut sections together to form the I-beam. To provide adequate anchoring of concrete decking to the steel girders, a regular array of mushroom-headed steel studs is welded to the uppermost flange of the girder, as shown in Figure 3 (*10*). When the steel welding operation is performed manually, the stud positions must be marked before the welding operations can start. The marking is time-consuming: it is estimated that it takes one-third of the time attributed to the whole operation. When the process is automated, it does not require premarking. The welding (usually) takes a long time since there are typically 400 studs welded to one girder. Throughout the operation, the welder has to carry the gun, which is tiring and hazardous (*10*).

A tracking mechanism is needed to move the robot along the girder because girders are usually several meters long. In this case, the tracking means required to guide the robot along the girder can be obtained by direct use of the girder, as shown in Figure 4 (*10*). This welding application can be extended to the welding of splices and braces.

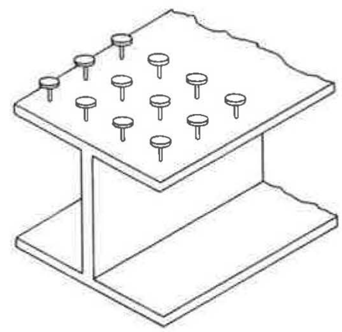

FIGURE 3 Array of steel studs welded to girder flange (*10*).

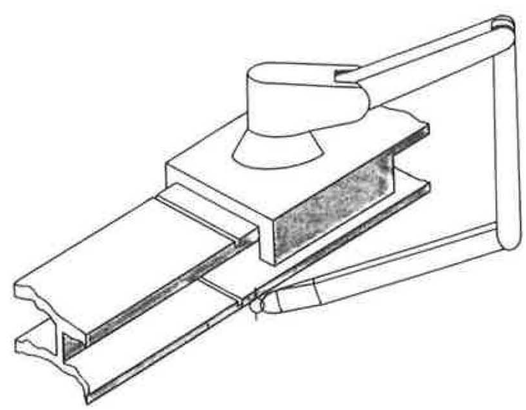

FIGURE 4 Robot setup for welding steel girders (*10*).

Bolting Connections

In railway bridges and in steel bridge work involving bolt and nut fastening, a robot similar to the one used for welding operations can be used. The effector at the end of the arm can be facilitated for gripping the bolt and tightening it into the nut, which is previously welded at the exact intended location by the welding effector.

Corrosion Protection

One of the most promising and cost-effective applications of robots has been shown to be surface finishing work. Basic surface operations include the following:

- cleaning and shaping (applying mechanical treatment to a raw surface to obtain better quality or utility); and
- coating and spraying (spreading a liquid substance on a structural surface to obtain better quality).

These repetitive and often hazardous tasks require protective equipment, continuous control, and high accuracy (*11*). As pollutant loads increase in air and water, and the threat and effects of acid rain increase, corrosion protection of steel facilities becomes a critical rehabilitation need.

The sandblasting process requires high-pressure spraying of air, water, or dust, which poses high risk to personal injury and requires expensive protection gear (*12*). Medical and statistical evidence claim that sandblasting processes pose a serious health hazard associated with lung silicosis to human operators. Sandblasting contractors estimate that the replacement of human labor with an autonomous robotic machine would result in an economic gain of up to 40 percent of the average human labor cost (*13*).

Sandblasting work is a highly specialized business with a multimillion-dollar turnover, in which productivity and efficiency are affected by human performance. Sandblasting jobs are tedious—typical maximum worker productivity is for only 4 hours a day. Overall daily productivity goes down by about 20 percent if the temperature is over 30°C (*13*). Robotization of sandblasting would result in the displacement of sandblasting crews by robot operators and possible savings in money for the contractor. These factors have been used as justification for introducing robots in surface finishing work (*11*).

Concrete pavement slab finishing work can also be a good application because this work involves long curing periods that force workers to work around the clock in tedious circumstances. A better-quality finish can also be expected with the use of robots.

Painting of Bridges

Painting bridges at high elevations requires costly scaffolding, which can be avoided by using a robot similar to the welding robot described earlier. The use of a robot also reduces the hazard of worker death by falling, which is a major cause of deaths in civil engineering operations.

A robot system that can climb up formwork rods to work at high elevations has been developed by the Fujita Corporation in Japan. The Climbing Jack Robot system is a robotized hydraulic jack equipped with a level detector and operating control device that grips and climbs a steel pipe rod. This system has been successfully applied in bridge pier construction. Currently, nine bridge piers have been constructed using this robot (*14*).

There is a great need for surveying and diagnostic tools that can provide condition and damage assessment information at reasonable prices to aid rehabilitation and repair efforts. It is clear that such tools have to be automated to provide quickness and accuracy in the operations. The ability of the tools to measure subsurface data will be invaluable in detecting and avoiding imminent failure of concrete pavement components. These operations are dependent on local factors and they demand equipment that is "flexible," "intelligent," and accurate. It is clear that automated data acquisition techniques coupled with robotics is the best answer to this need. Robots are also needed to carry out inspection work in inaccessible and dangerous locations. Some potential applications are discussed below.

Inspection of Concrete Pavements

Researchers at Carnegie-Mellon University, Pittsburgh, Pa., have developed a robot to evaluate existing reinforced concrete pavements. With its sensors, the robot checks the condition of reinforcing steel in the pavement and transmits data to a computer or video screen. Engineers are immediately able to detect the condition of the reinforcing bars in a nondestructive manner (*15*). This robot has sensors embedded in its base plate to indicate reinforcing bar location and size and the quality of concrete and how well it meshes with the subsurface (*15*).

By using sensors, robots can also be made to detect cracks, potholes, and warping on concrete pavements. These methods can be used without having to disrupt traffic for long.

In prestressed concrete beams, it is difficult to detect the exact location of steel elements. Robots could be used to hold up the steel elements in proper profile during the entire concrete pouring operation. Other applications are point-of-placement concrete quality testing and continuous weld quality monitoring.

Currently computers are doing some of the potential robot applications in this area. Ground-penetrating radars are used to detect voids under a jointed concrete pavement and a microprocessor-based system is used to conduct a road survey. This survey can be done at the rate of 5 lane-miles of pavement per hour with only minimal interruption of traffic (*16*). This survey information can be made available to robots for efficient location of voids. Recognition of displaced dowel bars, reinforcing bars, and prestressing tendons are other microcomputer-based technologies that can make robotization more versatile.

Fabrication of Steel and Reinforcing Bars

Robots are routinely used in the manufacturing industry for cutting operations. Steel elements for fabrication of bridge trusses can be accurately cut to the required specifications and configurations by using a robot.

Reinforcing steel fabrication is also possible with a robot. A reinforcing bar (rebar) robot will take rebar from a spool and cut, hold, bend, and weld the rod to any shape designated by a computer (*15*). These steps eliminate tedious and slow work usually associated with unwinding and cutting reinforcing bars, which also generates considerable cost savings.

Concrete placing has also been robotized. The Takenaka Corporation in Japan has developed the Horizontal Concrete Distributor, which has solved diverse problems involving moving the end-hose and relocating pipes, tasks that are labor intensive. The operating system of the robot is intelligent and sufficiently flexible to respond to any command given by the operator regarding the direction of movement. This robot has been applied widely and has enabled placing a total of 120,000 m^3 of concrete at more than 20 sites since 1981 and is still being improved for higher efficiency (*17*).

Other robots designed for concrete slab-finishing, e.g., MARK II (*18*) and SURF-ROBO (*19*), are also being employed successfully. The MARK-II robot was developed by the Kajima Corporation in Japan and is, technologically, fully developed to the current state of the art. It can be operated even by workers instead of engineers and is expected to find wide use.

SURF-ROBO has the capacity to finish a concrete floor surface of 300 m^2 per hour with the same finish and accuracy of a plasterer. Ten such robots are being used by the Takenaka Corporation in Japan at practically every one of their construction sites.

Excavation Work

Excavation is an excellent application of robotics because of its significance in scale and economic importance. Excavation operates on a universal and generic material (soil) and its goal and state can be adequately described by models of geometry and kinematics. Such diverse robotic excavation applications as off-shore ocean floor construction, pipe excavation for utilities, and repair of bomb-damaged runways are emerging (*20*).

A Robotic Excavator (REX) was first designed by researchers at Carnegie-Mellon University. REX integrated sensing, modeling, planning, simulation, and action, specifically to unearth buried utility piping. REX reduced the excavation hazard posed by explosive gases, decreased operation costs, and increased productivity. Soil was gently cleared as excavation progressed until the buried object was discovered (*20*).

A second-generation excavator developed later is a refinement on REX and is called GENEREX. This machine has better refinement in sensing because of the use of multiple sensors to acquire raw visual, tactile, and magnetic sensory data (*20*).

Magnetic sensing capabilities are important for detecting underground human-made objects such as buried pipes and cables. Robots equipped with such sensors will be able to distinguish buried pipes and cables from other buried objects such as tree roots and debris.

This application has special potential since major excavation activity is proposed to be done on the roadways all over the United States to replace conventional utility cables with fiber optic cables. Introduction of robots for excavation in such activities will reduce the cost per mile of these cable installations and make them more attractive to the utility companies and consumers.

Another important advantage in robotizing excavations is in the reduction of the number of deaths of workers because of cave-ins of excavated material. More than half of all construction accidents involve trenching and excavation, and there are hundreds of such fatalities every year; in addition, there are thousands of accidents in which people are injured and untold thousands of accidents in which no one is hurt but from which there is significant economic loss (*21*). These accidents happen because of assumptions that if a trench or excavation bank stands after the excavation is dug, it will continue to stand. Earth banks may have varying stand-up times ranging from a few minutes to several months, but cave-ins are not easily predictable.

In situations where deep excavations are needed, there is a need for long reach. Manipulators with a long reach have been designed for civil engineering applications (*22*). These manipulators have a reach of up to 52 m, with a capacity of 200 yd^3 per hour and are equipped with video data acquisition techniques (*22*). Such robotic arms can be used in large excavation work involving deep trenches since they help avoid hazards and also have a good output per hour.

Another possibility is to incorporate laser grading apparatus with these robotic arms to enable automated excavation grade control. These machines substitute for lower-cost machines (such as bulldozers and motor-graders) and low-skilled operators while yielding high-quality improvements (*23*).

A robot for real-time measurement of the degree of soil compaction has been developed for new pavement construction (*24*). This is a self-propelled robot with the unique capability of position measurement for guiding itself. A design has been proposed for a robot that performs pavement-cutting work (*25*) that can decrease the accident risk, noise level, and pavement surface slurry contamination.

Tunneling Operations

Tunneling operations often take place in dangerous situations involving cave-ins, the presence of hazardous gases, flooding water, and suffocation of workers. Workers perform strenuous and difficult jobs during tunnel excavations that are slow, thus lowering the quality and productivity rate. During tunneling operations, it is essential to furnish fresh air at the rate of 200–500 ft^3 per minute per worker and to remove noxious gases and fumes produced by explosives. It is also necessary to remove the dust caused by drilling, blasting, mucking, and other operations because silica dust causes lung diseases in workers (*26*). These tasks are not only costly but require enormous safety precautions.

Tunnel excavations can be performed quickly by a preprogrammed robot that ensures accurate alignment and extent of digging. Further, robots can work around-the-clock without getting exhausted.

The Japanese have developed automatic recorders attached to advanced soft-ground tunneling machines to record excavation volumes, advance rates, jack pressures, and other parameters to guide a "blind" tunneling operation (*2*).

Shotcreting is another robot application in tunneling. In the Austrian tunneling method, shotcrete applications take as much as 30 percent of the total time. Kajima Company in Japan has developed and implemented a computer-controlled applicator by which high-quality shotcrete is placed quickly (*11*).

Robots with vision sensors can detect defects in linings and jointing. End effectors can be used for spraying, grouting, and caulking operations in tunnel lining work.

A new automated tunneling method (M2) has been developed that is suited to underground conduit laying in congested heavy-traffic areas (*27*). This enables automatic transportation of excavated soil and lining material in the tunnel by an unmanned system. A 170-m resin tunnel under a public road has been successfully constructed in Japan by the M2 method.

A robot developed to inspect the inner linings of piping at a nuclear power plant helped shorten inspection work schedules by about 40 percent and helped reduce costs by 30 to 40%. This remote-controlled system reported the conditions of in-pipe scales and the condition of the inner lining (*28*).

Roadside Management

Each year the Department of Transportation in various states spends thousands of dollars in roadside maintenance. These operations include grass cutting, weed control, herbicide spraying, drainage inspection, and culvert maintenance. Some of these operations can be robotized for productivity improvements in automated roadside maintenance systems. Work inside culvert pipes having small diameters is difficult since they are not easily accessible. The inner linings of culvert pipes can be inspected by a robot that can identify the exact locations of damage. The same robot can be used to correct the damage in those locations by using appropriate end effectors.

Herbicide spraying is usually done manually or with the help of tractors. The chemicals used in the spray can cause harm to the lungs, skin, and eyes of workers. Robotization of this operation can reduce this hazard while improving productivity. Grass-cutting capabilities can also be incorporated into this robot, which can be equipped additionally with a laser grading device—another robot application for roadside maintenance.

Some other applications suggested for robots include underwater repair, changing lamps on lampposts, washing signs and luminaires, servicing vehicles, performing security patrols, and fabricating signs in the shop (*29*).

Robots also have the advantage of working silently compared with conventional equipment, thus reducing noise pollution around worksites.

Handling of Hazardous Waste Material in Preparation for Transportation

The issue of hazardous material handling is generating a lot of attention and research in the United States. Research has shown that robots can be used for cleanup of radioactive sludge from nuclear plants (*2*) and for maintenance and remote operation of nuclear spent-fuel processing plants (*30*). These applications can be extended to hazardous material handling operations associated with hazardous material transportation. As new roadways are built, chances of encountering hazardous waste dumps and landfills increase. Operations under these conditions require expensive protective gear and complex precautionary measures that can be substantially reduced if robots are used for excavation. Computers are helping to maintain an efficient hazardous materials transportation information system to report incidents of hazardous material releases (*31*). A computerized aerial photographic analysis has proven to be a highly cost-effective and accurate predictor of the location of hazardous waste contamination. Aerial photographs are used as inputs to a digital mapping system and the overlays are generated to identify specific configurations of the clean-up sites (*32*).

Railway Track Maintenance

Railway tracks must be inspected and maintained regularly to provide safe and efficient operation of the railway system. Robots can be used to inspect sleeper bolt connections, fish plates, cracks in old rails, and railway bridge structures. Vision sensors would be of use in this application. Robots can also be employed to weld corroded and cracked rails.

Some other robot applications in railways are sequence operations in shunting yards; building and repair operations of traffic structures, including application of multiple spindle screw machines, sleeper bolt screws, etc.; transportation, transfer, and storage processes in automatic transportation systems, for the automation of stock-keeping or handling of installations (e.g., for wagon unloading), and service processes for transportation facilities with a special emphasis on cleaning devices (*33*).

Interfacing with Digital Mapping Systems

Surveying and mapping have traditionally played a central role in all phases of an engineering project. In the 1980s, the need for computerized graphic data bases has prompted the development of geographical information systems (GIS) and satellite surveying techniques such as the Global Positioning System (GPS) for real-time operations. It is predicted that the development of real-time surveying and mapping techniques will achieve top research priorities in the next decade. Supported by vision systems such as GPS, vital functions such as construction layouts, inspection, change detection, and quantitative measurements as well as robot guidance can be done (*34*). Digital mapping systems such as ENMIT allow for graphic information on roadside management planning. ENMIT facilitates identification of damaged roadside vegetation and wetlands from a large geographical data base (S. M. Naik and W. C. Hall, Unpublished data, 1989). The information derived from such a data base can be used to guide robots meant for roadside maintenance. State agencies proposing to invest millions of dollars in GIS software and hardware in the near future will find that robots can derive guidance for field operations from these systems.

Space Applications

The successful use of a robotic arm to retrieve a nonfunctional satellite from its orbit for repair by a U.S. space shuttle has demonstrated the need for robots in space transportation operations. As civil engineers prepare to discuss their role in space exploration and exploitation (*35*), the need for robots in planning, maintenance, and operation of facilities in space will be further emphasized.

USE OF EXPERT SYSTEMS FOR ROBOT TASK PLANNING

Robotization of transportation operations will definitely bring about changes in the planning approach of engineers. Because equipment operators are inexperienced in the handling of robots and because they and managers are familiar with traditional techniques only, managers are concerned about their ability to oversee robot-related tasks in the construction process. Managers may fear low productivity from robots and delays that may affect the cost and duration of projects.

Computer-aided design and drafting has revolutionized the civil engineering industry. This technology has successfully been performing some of the potential robot applications discussed in this paper. The processes of analysis, evaluation, and synthesis of design data can be shared in an interprocess communication system (*36*). Automated data acquisition for field operations is performed with the use of minicomputer-based recording and monitoring instruments. Automated monitoring of construction quality control, production rates, and quantities is being done with the use of time-lapse photography, laser guidance systems, remote sensing, and GIS. These technologies can be used as supplements to robots to make them more versatile. Methods of using artificial intelligence techniques such as knowledge-based expert systems have been suggested to generate construction plans suitable for the constraints and conditions of robotized construction. These are used to create a model to serve as a data structure for poorly designed construction plans and schedules (*37*).

Pavement management systems are becoming increasingly useful microcomputer-based tools. These maintain a large data base of meaningful information on roadway deficiencies. Condition survey information based on foremen's evaluations of highway deficiencies are used in conjunction with parameters such as average daily traffic, pavement type, the level of resurfacing needed, and the condition of the shoulder to help keep roadway maintenance costs low.

The most significant research effort in computers related to robotics has been the advancement in machine vision. The advantages of vehicle detection through image processing are several. Image processing can simultaneously detect traffic, derive traffic measurements, perform surveillance, and recognize special vehicles. It accommodates future advanced truly dynamic control strategies for both arterial networks and freeway corridors (*38*).

Recent research in machine vision has presented three-dimensional machine vision, enabling measurement of light intensity and, thereby, distinctions between colors and textures. In spite of the complexity of machine vision systems, the field is booming today. A representative vision module, designed to supplement a robot system, costs from $15,000 to $40,000 and is expected to cost less as the industry matures (*39*).

The growing field of expert systems has continued to offer many benefits to the transportation industry. Scheduling, cost control, estimation of quantities, intersection design, feasibility analysis, structural analysis, and environmental management are just a few of the applications of expert systems in transportation.

Expert systems can enable robots to decide between multiple alternatives in motion and choice of action. An expert system framework for decision making on implementing robotics in construction has been proposed (*40*). The system's reasoning synthesizes available decision-support tools and considers technical and economic criteria for its decisions. Implementing this system will be useful when, in the future, construction robotics designers need feedback.

MANAGERIAL AND SOCIAL PROBLEMS OF INTRODUCING ROBOTICS IN TRANSPORTATION ENGINEERING

The introduction of robots in transportation engineering will definitely cause significant changes in the transportation sector as a whole. Although productivity, performance, and cost savings show potential dramatic increases with robotization, there are also several inhibiting factors.

Construction is an unfamiliar area for robot manufacturers. An April 28, 1983, *Engineering News-Record* report on the 13th International Symposium on Robots states, "of the 260 robots on display, . . . not one was earmarked for construction applications" (*41*, p. 30). Furthermore, conference exhibitors were unaware of any jobsite applications in the United States.

Another problem is that robot manufacturers are reluctant to push forward this technology. They insist that many basic and developmental problems need to be resolved before robotics can play any significant role in construction. To begin with, manufacturers do not have a complete understanding of the demands of the highway construction environment. According to one manufacturer, the Swedish ASEA company, "construction jobs are not always the same. So there's not a great deal of repeatability. Most construction jobs require a certain amount of on-site judgement, which a robot cannot provide. And if I leave a robot out in the rain, I lose $100,000 by the end of the week" (*41*, p. 32). One university researcher observed that development in the construction industry is driven by the marketplace and application is limited to locations of high hazards such as radiation, toxic wastes, and explosives (*41*).

Further, there is very little research in the construction industry. The main reason why Japan has been able to robotize construction operations is because robotics research is done by the construction industry itself. Companies like Shimizu Construction Company, Kajima Corporation, and others have developed robots for construction tasks and are using them successfully in the field (*18*, *25*). Robot manufacturers have not been shown that construction is an attractive field for robotization. They agree that they are too busy chasing the industrial market to go after unknowns in construction (*41*). Social and economic barriers such as fragmentation of the industry, risk and liability, and lack of standards and codes are also cited as obstacles to this advancement (*6*). "Intelligent" robots developed to adapt to changing environments rather than to structured environments are preferred over present-day robots because they allow the benefits of applying artificial intelligence and expert systems research to best emerge. Major factors inhibiting robotization can be unemployment of personnel displaced by robots, work capitalization for specialty subcontractors, unpredictability related to a new technology, risks of litigation, and inadequate funding for further research.

Major factors encouraging robotization can be the increasing awareness of the need for better productivity and performance for survival in a fiercely competitive international and domestic market, the dearth of human skill, the slow growth of research, and marketplace challenges for better performance.

Management is also becoming more flexible as managers bring better educational backgrounds and skills into managerial positions. However, a cautious response to robotization from worker unions has to be expected as the field of civil engineering adopts and adapts itself to robotization.

More fundamentally, the introduction of new technology (such as robots) brings with it the prospect of revamped construction procedures at the site, which promise radical improvements in productivity and working conditions. Not only will labor skills need to be upgraded, but also the labor-machinery interface will need to be revised; indeed, the entire structure and planning of construction activities may require rethinking.

SHORT-TERM GOALS FOR ROBOTICS IN TRANSPORTATION

As recognized in this paper, research in robotics is forthcoming, although slow. Further, most of the research is being done in Japan and by their construction industry itself. This needs to be emulated by the construction industry in the United States.

Further advancement in machine vision, expert systems, natural language processing, neural networks, and network communications are near-term goals beneficial to robotics. The construction material industry should manufacture structural components suitable for assembly by robots in a manner similar to that of the automotive industry. This type of system would facilitate the increase in the variety of robots assembled by the robot manufacturers. An efficient nationwide network of "build-to-assemble" component industries and local distribution of such components would parallel the distribution of robots.

The most important short-term goal is the synthesis of all robotics-related data to form a comprehensive knowledge base. This system should contain knowledge of not only the technology but also the input data suitable for available robotic systems. The types of data include numeric, graphic, and image with access to on-line construction data bases. Such a unification of knowledge would disseminate awareness about robotics among transportation professionals.

The idea of using robots is slowly being accepted by transportation research committees. A forthcoming conference on advanced technologies in transportation engineering has set aside a separate tutorial session on robotics. This trend should be strengthened so that all research organizations recognize the urgency to stay abreast in this promising technology.

CONCLUSIONS

The benefits of adopting advanced technologies in transportation have been inadequately recognized so far, resulting in overlooking possibilities to make substantial and important changes to infrastructure maintenance and rehabilitation work.

At current levels of progress, this work will be expensive in terms of time and cost. Hence, there is a great need for a radical change in the methods, materials, and equipment used in the construction, rehabilitation, and maintenance of transportation facilities. Successful automation in various areas has demonstrated the reliability and cost-effectiveness of using robots. Hence, much of the future growth in transportation must be in adopting new technologies, among which robotics is important and attractive. To make progress, robot manufacturers must envision that robots must handle construction jobs under uncontrolled and harsh environments, such as the extreme winter cold in Alaska, and sandstorms and 120°F heat in the Middle East. They work at high elevations during winter, and on road clearing and repair operations under snowy conditions. These are situations in which workers can get welcome relief from harsh conditions and the risk of fatal accidents. Robot manufacturers are right when they present the basic and developmental problems that need to be resolved before automated data acquisition, robotics, and process control technologies evolve to the point at which they will play a significant role in the transportation sector. Many of these problems could form exciting long-term basic research topics if researchers are made aware of the potential of these technologies. Focusing the attention on high-technology research in this area requires considerable mutual understanding with researchers in other high-technology fields, with the major initiative coming from civil engineers. A sincere effort is needed on the part of the government, research agencies, universities, and private industry to evolve a systematic and vigorous research effort to advance the trend of research in transportation engineering robotics.

REFERENCES

1. Fundamental Research on Transportation Facilities: Workshop Report. *Transportation Research*, Part A, Vol. 19A, No. 5/6, 1985, pp. 495–496.
2. Japan Takes Early Lead in Robotics. *Engineering News-Record*, July 21, 1983, pp. 42–45.
3. D. E. Boyce, ed. Transportation Research: The State-of-the-Art and Research Opportunities. *Transportation Research*, Part A, Vol. 19A, No. 5/6, 1985, pp. 349–550.
4. Fundamental Research on Transportation Facilities: Workshop Report. *Transportation Research*, Part A, Vol. 19A, No. 5/6, 1985, pp. 495–496.
5. F. Moavenzadeh. Research Needs in Transportation Facilities: Guideway Technology and Materials Research. *Transportation Research*, Part A, Vol. 19A, No. 5/6, 1985, pp. 497–509.
6. K. C. Sinha, L. F. Cohn, C. T. Hendrickson, and Y. Stephanedes. Role of Advanced Technologies in Transportation Engineering. *Journal of Transportation Engineering*, Vol. 114, No. 4, July 1988, pp. 383–392.
7. W. L. Whittaker. Construction Robotics: A Perspective. *Proc., Joint International Conference on CAD and Robotics in Architecture and Construction*, Marseilles, France, 1986.
8. A. Warszawski and D. A. Sangrey. Robotics in Building Construction. *Journal of Construction Engineering and Management*, Vol. 111, No. 3. Sept. 1985, pp. 260–268.
9. *Specification of Industrial Robots in Japan*. Japan Industrial Robots Association, Tokyo, 1981, pp. 31–33.
10. P. Drazan. Application of Robots in the Construction Industry: Navigation of a Mobile Robot, Robotic Welding of Steel Bridge Girders. *Proc., Joint International Conference on CAD and Robotics in Architecture and Construction*, Marseilles, France, 1986.
11. M. J. Skibniewski and C. Hendrickson. Analysis of Robotic Surface Finishing Work on Construction Site. *Journal of Construction Engineering and Management*, Vol. 114, No. 1, March 1988, pp. 53–61.
12. K. A. Chandler and D. A. Bayliss. *Corrosion Protection of Steel Structures*. Elsevier Applied Science Publishers, London, 1985.
13. M. J. Skibniewski. *Engineering and Economic Analysis of Robotic Application Potential in Selected Construction Operations*. Ph.D. thesis, Carnegie-Mellon University, Pittsburgh, Pa., 1986.
14. W. Isomura, S. Morimoto, and K. Sato. Application of a Climbing Jack Robot System. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 477 482.
15. Robots Coming to Jobsites. *Engineering News-Record*, Feb. 10, 1983, p. 113.
16. G. G. Clemena, M. M. Sprinkel, and R. R. Long, Jr. Use of Ground-Penetrating Radar for Detecting Voids Under a Jointed Concrete Pavement. In *Transportation Research Record 1109*, TRB, National Research Council, Washington, D.C., 1987, pp. 1–10.
17. H. Aoyagi and Y. Shibata. Development of the Horizontal Concrete Distributor for Concrete Placing. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 541–550.
18. K. Arai, B. Yamada, M. Saito, and K. Banno. The Development and Practice Test of the MARK-II. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 551–555.
19. K. Kikuchi, S. Furuta, and T. Imai. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 561–565.
20. W. L. Whittaker and B. Motazed. Evolution of Robotic Excavator. *Proc., Joint International Conference on CAD and Robotics in Architecture and Construction*, Marseilles, France, 1986.
21. L. J. Thompson. Trenching and Excavation Safety. *Proc., Specialty Conference on Construction Equipment and Techniques for the Eighties*, ASCE, New York, 1982, pp. 302–307.
22. M. C. Wanner, H. Heidemann, R. Hoffmann, and R. Konig. Design of a Manipulator with a Very Large Reach for Civil Engineering Applications. *Proc., Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction*, Haifa, Israel, 1987.
23. B. C. Paulson, Jr. Control of Construction Equipment Processes. In Microcomputer Within the Urban Transportation Environment. *Proc., National Conference on Microcomputers in Urban Transportation*, San Diego, Calif.; ASCE, New York, 1985, pp. 729–738.
24. T. Umezono, N. Yakagawa, T. Takada, H. Sakurai, A. Shimazu, and K. Minami. Measuring Robot of the Degree of Soil Compaction. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 811–819.
25. T. Kobayashi and S. Honda. Study on a Robotic System for Pavement-Cutting Work. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 289–295.
26. R. Peurifoy. *Construction Planning, Equipment and Methods*, 4th ed., McGraw-Hill Book Co., New York, 1985.
27. S. Kondo, K. Matsuzaki, and M. Kuroiwa. Automatic Shield-Tunneling Method with a Small Cross-Sectional Area. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 859–866.
28. K. Ozawa and K. Kato. Application of In-Pipe Visual Inspection Robot to Piping Internal Surface Lining. *Proc., 5th International Symposium on Robotics in Construction*, Tokyo, Japan, 1988, pp. 859–866.
29. W. Zuk. *Robotics in Construction*. Technical Report VHTRC 85-R38. Virginia Highway and Transportation Research Council, Charlottesville, Va., 1985.
30. H.-R. Oeser. Femo Technique: A Milestone for Remote Operation and Maintenance. *Proc., Joint International Conference on CAD and Robotics in Architecture and Construction*, Marseilles, France, 1986.
31. M. Abkowitz and G. List. Hazardous Materials in Transportation Incident-Accident Information Systems. In *Transportation Research Record 1148*, TRB, National Research Council, Washington, D.C., 1987, pp. 1–8.
32. T. L. Weck. Hazardous Wastes Within the Transportation Planning Context. In *Transportation Research Record 1148*, TRB, National Research Council, Washington, D.C., 1987, pp. 62–67.
33. P. Kopacek, Robotics in Transportation. Control in Transpor-

tation Systems (1986). *Proc., 5th IFAC/IFIP/IFORS Conference*, Vienna, Austria, 1986.
34. K. W. Wong. Surveying and Mapping Beyond 2000. *Journal of Professional Issues in Engineering*, Vol. 114, No. 3, July 1988, pp. 281–286.
35. Space '88 Set for August Launch. *ASCE News*, Vol. 13, No. 7, July 1988, p. 13.
36. D. R. Rehak and H. C. Howard. Interfacing Expert Systems with Design Databases in Integrated CAD Systems. *Computer-Aided Design*, Vol. 17, No. 9, 1985, pp. 443–454.
37. N. Kano. An Expert System for Planning in Robotized Construction. *Proc., Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction*. Haifa, Israel, 1987.
38. B. C. Paulson. Automation and Robotics for Construction. *Journal of Construction Engineering and Management*, Vol. 111, No. 3, Sept. 1985, pp. 190–207.
39. H. Katzan, Jr. *A Manager's Guide to Productivity, Quality Circles, and Industrial Robots*. Van Nostrand-Reinhold Co., New York, 1985.
40. M. J. Skibniewski. Framework for Decision-Making in Implementing Robotics in Construction. *Journal of Construction Engineering and Management*, Vol. 2, No. 2., 1988, pp. 260–271.
41. Robot Makers Building Shy. *Engineering News-Record*, April 28, 1983, pp. 30–32.

Publication of this paper sponsored by Commiteee on Construction Management.