Current Worldwide Status of Robotic Applications in Construction

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Worldwide, small-scale robotic construction applications have existed for approximately 3 decades. Government, universities, industry (e.g., construction companies and construction equipment manufacturers), research laboratories, and research institutions have all been involved and are still pursuing work in the application of robotics in construction. The participation of different countries in this area is summarized; only those countries that have been comparatively active in their efforts are included. On the basis of analysis and some field observations, the author concludes that the Japanese are advanced in the application of robotics in construction. However, worldwide efforts, cooperation, and dedication are needed to improve, develop, and capitalize on the potential worldwide benefits of construction robotization.

During the past 3 decades, the field of robotic applications in construction has challenged relevant government construction participants, the construction industry, construction equipment manufacturers, construction engineering firms, and the engineering academic community. In the United States, the government is transferring research and development activity to industry and the community through technology transfer programs. Although budget constraints are slowing these efforts, great emphasis is being placed on the importance of technology transfer programs. The number of robots in the United States grew from 200 in 1970 to more than 100,000 at present. There are 20 to 25 academic research centers and government laboratories, along with a similar number of commercial enterprises, that experiment with robots. The volume of government-sponsored research in robotics in the United States was about $20 million in 1982 (*1*). However, according to a January 1992 CBS Evening News television report, the United States lags behind Japan, Germany, and Sweden in related research.

In the United States, robotics development efforts are focused on such new technologies as artificial intelligence, robotics vision, and parallel processing computer architecture (*2*).

Robotization investments have been made by the Japanese manufacturing industry since the mid-1970s. The tendency of young Japanese people to not work in construction created a labor shortage that forced government and industry to progress further in robotization. The Japanese are aggressively looking at the long-range future benefits of robots in the construction field.

In Europe, progress of automation and robotics in construction has not been particularly aggressive. Economic problems in Europe and Australia have slowed progress in this field. In general, close coordination among the active European countries, Australia, United States, and Japan is essential for ensuring successful technology transfer. Traditional sources of government funding in these countries could be used to support joint research and development of construction automation and robotics. Sources of financial support in the United States include the National Science Foundation, National Aeronautics and Space Administration (NASA), U.S. Department of Defense, Associated General Contractors of America, Construction Industry Institute, American Road and Transportation Builders Association, and Construction Industry Manufacturer's Association. Most private associations are not active in promoting robotics technology among their members.

Most of Japan's robotic research was begun at Waseda University System Science Institute in 1978; the program is supported by private and public funding. Japan's Ministry of International Trade and Industry and the Industrial Robot Association specifically identify and support construction-related activities that can be performed by robots (*3*). In Australia and Europe, most support comes from government sources.

STATUS OF CONSTRUCTION AUTOMATION AND ROBOTICS

United States

Examples of some of the robots built in the United States are presented in Table 1 (*4*). Many universities are currently conducting robotics research, including the University of Florida, Purdue University, University of Texas at Austin, North Carolina State University, University of Illinois at Urbana-Champaign, Ohio State University, University of Colorado at Boulder, University of Wisconsin at Madison, and Texas A&M.

The U.S. Army Construction Engineering Laboratory is also interested in automation, particularly for the cleanup of hazardous or toxic materials.

Japan

In Japan during the past 15 years, efforts have been made by general contractors to integrate joint development for building construction robots. The Japanese realize the importance of close cooperation and coordination among general contractors, robot manufacturers, lease or rental companies, and subcontractors. They recognize that cooperation and coor-

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TABLE 1 Examples of Robotics Developed in the United States (4)

Robot Type	Application	Developer
John Deere Excavator, Model 690C	Teleoperated excavation for rapid airport runway repair	John Deere, Inc., Moline, Illinois
Laser-Aided Grading System	Automatic grading control for high-volume earthwork	Gradeway Construction Co. & Agtec Development Co., San Francisco, California; Spectra-Physics Co., Dayton, Ohio
Automatic Slipform Machines	Placement of concrete sidewalks, curbs and gutters	Miller Formless Systems Co., McHenry, Illinois; Gomaco, Ida Grove, Iowa
Micro-Tunneling Machine	Teleoperated micro-tunneling	American Augers, Wooster, Ohio
Robotic Excavator ("REX") and Autonomous Pipe Mapper	Autonomous excavation around buried utility metallic pipes, potentially for several types of autonomous nondestructive testing	Carnegie Mellon University, Pittsburgh, Pennsylvania
"NavLab"	Autonomous navigation in unstructured terrain	Carnegie Mellon University, Pittsburgh, Pennsylvania
Remote Work Vehicle	Nuclear accident recovery work, demolition of structures after nuclear accidents, structural surface decontamination, cleanup and treatment, transport of materials	Carnegie Mellon University, Pittsburgh, Pennsylvania
"Wallbot," "Blockbot," Shear Stud Welder	Construction of building interior partitions with metal track studs, concrete masonry work, welding of shear connections in composite steel/concrete structures	Massachusetts Institute of Technology, Cambridge, Massachusetts
Automated Pipe Manipulator	Teleoperated pipe system assembly in industrial processing plants	University of Texas, Austin, Texas
Automatic Pipe Bending System	Robotic bending and connection of metallic of pipe sections	University of Texas, Austin, Texas
Experimental Maintenance Device	Automated pavement crack sealing	Carnegie Mellon University, Pittsburgh, Pennsylvania

dination are the key concepts in a successful construction robotization program.

More than 40 major construction companies in Japan are active in robotics development and application in construction. For instance, Shimizu has now developed a multipurpose vehicle called MTV1. It includes a powered mobile-control module, sensors, navigation devices, and controllers, and it performs various floor-finishing operations (3).

In June 1992, the author attended the 9th International Symposium on Automation and Robotics in Construction (ISARC) in Tokyo, Japan, and visited the Landmark Tower in Yokohama, which was under construction. This is a new city center for Yokohama with a building area of 253,011 ft^2, 3 floors below ground, and 70 floors above ground, with a steel frame and reinforced concrete structure. Robotics applications on this site included a directional controlled lifting system, a remote shackle, manipulators for placing steel doors and aluminum curtain walls, an automatic lifting system for materials for finishing work, and an automatic positioning system for the steel frame building block. The automation and robotics in construction application on this site was quite impressive and cost-effective in terms of safety, liability, and labor shortages. It was evident that the Japanese are quite successful in using robots in construction of buildings, foundation work, lifting operations, uniform finishing of concrete floors, automatic paint spraying of exterior walls, finishing jobs, and plasterboard positioning in which the robot picks up individual panels and moves them to a preprogrammed position for ceiling installation. Robots are also used for lifting and erecting heavy precast concrete panels. In addition, robots are used for tunneling. For example, the Shimizu company presented a video to the conference members showing a tunneling shield equipped with a steering mechanism between the rotating cutting wheel and the bulkhead. This allows the machine to be steered precisely, reducing excavation volume and allowing segment placement to progress alongside excavation.

Another product is a submarine shield that has a connecting mechanism that allows long undersea tunnels to be excavated without the need for an excess shaft where the two tunnels from each shore meet. Another machine is used in tight spaces, such as shafts, for tunneling and building foundations to position the heavy braces that support cofferdams. The Japanese have also developed automatic concrete surface scabbles to scabble the surface of vertical construction joints; these machines scabble the concrete surface of bridge piers reinforced for road expansion 20 times faster than hand-held machines. Another product is an automated formwork that can be elevated without a crane. The dam concreting system, consisting of a mobile tower crane, bucket carts, and transfer cars, transported concrete and workers efficiently and safely. Many cranes are built with a control system that is made of a collision prevention system and an operational management system for erecting heavy steel frame in tall buildings.

The Japanese have also built an automated glass roof washer that safely cleans vast slanted glass roofs. In another video presented at the conference, a biological shield concrete-cutting robot was used to dismantle the concrete structure surrounding a reactor while people remained at a safe distance to avoid radiation.

The new generation of robots has the potential to reduce human resource requirements, enhance productivity, and perform hazardous and repetitive work. Japanese experts believe that the Japan Ministry of Construction, Ministry of International Trade and Industry, Tukuba University, Japan Building Contractors Society, and the U.S. Construction Industry Institute are important organizations that could enhance construction robotization. These organizations should extend and coordinate their research activities with those of organizations in Europe and Australia.

Germany

The Germans do not have an overall aggressive robotics development program and approach comparable to the one in Japan. However, construction-related developments include the following (*5*).

- Excavation:
  - –Hydraulic pumps are able to control the energy in reference to the requirements;
  - –Computer-assisted loading with Teach-In and automatic excavation of that movement is used; and
  - –Computer-assisted profiling by means of an external sensor system and a specific controller is used.
- Earthwork equipment:
  - –Graders feature moldboard control (slope, angle, external control by laser) and front wheel electronic drive control;
  - –Loaders feature torque converters to optimize fuel consumption; and
  - –Dumpers feature power program for high-driving performance on difficult terrain.
- Road construction: road pavers feature automatic leveling, including controllers and servo valves to achieve better quality.
- Concrete distribution: enhanced functions of concrete distributors control large reach manipulators with a rotary axis.
- Telescopic cranes include controllers with the following features: load limitation control; measurement of the wind forces, with a warning to the operator; platform control; and test, diagnostic, and maintenance system.
- Concrete panel fabrication: a system that has achieved a high industrial standard and integrates design, time scheduling, and fabrication with highly automated stations. For the placement of reinforcement, two robots are in operation per plant.
- Brickworks:
  - –An outdoor handling system features simple small mobile cranes; and
  - –A stationary plant manufacturing system features automated placement of bricks and mortar.
- Tunneling: one major drive to robotics development could come from a coal mine application. Robots are used for inspection and repair of concrete sewers.
- Nuclear applications: robots are used for the decommissioning of nuclear power stations. Research efforts are directed toward further development of robotics in nuclear applications (*5*).

Sweden

In 1983 Sweden established the Swedish Construction Industry (SBUF) to promote development work in the construction industry. It was set up to be co-financed by the government, mostly by the Swedish Council for Building Research, with the goal of seeking further financial support from municipalities and the building material industry. By 1993 the yearly support for SBUF reached MSEK 70 (MSEK = million Swedish Crowns; $1.00 = 6 SEK). The support is preferably intended for research and development at technical universities. Seven areas of priority for research and development have been identified to be supported by this fund (*6*):

1. Material technology,
2. Information technology (robotics),
3. Mechanical services,
4. Indoor climate,
5. Facility management,
6. Infrastructure, and
7. Economizing of resources.

Robotics in construction in Sweden is applied to working tasks with a difficult construction environment such as demolition, tunneling, and handling of materials. Robotics are used for soil reinforcement works in existing buildings. Most robotics in use in Sweden are remotely controlled. The Swedes believe that success requires joint research and development—cooperation among contractors, manufacturers, and universities (*6*).

United Kingdom

The United Kingdom Advanced Robotics Programme was initiated in 1985 with the support of the Department of Trade and Industry. For tunneling, robots are used for segment erection and grouting of tunnel walls. In mines, a continuous system of temporary roof support robots is used that "walks" in space with a cutting machine, provided with a sensor-driven robotics control system for semi-autonomous tunneling within a coal seam (*7*).

In 1988 the Advanced Robotic Research Center at Salford planned to design robots that could operate in unstructured environments. This program has resulted in the lab-scale demonstration of the ability of robot systems to operate autonomously in unstructured environments. The program included

Advanced Robotic functional architecture, a manipulator general-purpose controller and free-ranging mobiles concentrating on the capabilities required for an indoor truly free-ranging Automatic Guided Vehicle (7).

At the City University in London, researchers continue to develop the enabling technology for automating masonry tasks in a quality assurance environment. The main functions of masonry construction were simulated in an experimental robot cell composed of a gantry-type robot that operates the grippers, material conveyor, and the laster beacon. The robot has been assisted by a supplementary navigation system to improve its positioning function. It is intended that a cell will be developed in which a mobile robot will replace the experimental gantry. In the experimental trials, construction of a dry wall was simulated because no provision was made for a mortar dispensing function, which has yet to be developed. The results so far have been encouraging, with emphasis on quality control, in particular in the assessment of the supply material (7).

Work on the inspection robot for nuclear reactors at the polytechnic of Portsmouth is progressing with the construction of three prototypes. The robot is joystick driven and pneumatically actuated. It has a 600-mm-wide and 150-mm-high control and moves on eight nonjointed legs with suction-cup feet. Using two frames with four feet mounted on each, it moves by disengaging one set of feet while the other set adheres. It carries lights and two cameras and can haul a payload of 25 kg. The robot is designed to climb about 10 m from the equator of the 20-m-diameter spherical reactor pressure vessel (7).

Automation of the inspection of tall buildings is the subject of research work at the City University in London (7).

A mini-excavator robot has been developed. The depth of a required trench is used as input; then the machine takes over and digs a high-quality flat-bottomed trench. A robot that provides soil strengthening by launching long reinforcing nails into the ground using compressed air is also commercially operational (7).

A recent report produced for the U.K. National Economic Development Council suggests that the adoption of Information Technology and electronic data exchange could cut overall building costs between 15 and 25 percent with similar or greater gains in productivity. At the University of Nottingham work has been in progress in automation of management functions and is moving closer to robot intelligence. Research topics include automatic generation and evaluation of plans and schedules, automatic budgeting and network generation, and layout optimism of building services (7).

Finland

The Technical Research Center of Finland (UTT) has been involved in research on construction robotics for several years. Still, construction robotics is in its infancy. UTT is supported by a federation of the Finnish building industry, of which all construction firms are members, and has established a system of cooperative research and development. A number of research committees, nominated by the federation, initiate and fund contract research projects, which are carried out by UTT, universities, and consultants. The major research themes are codes and information files, construction management systems, production technology, product development, and personnel development. One such program supported by UTT is the Logistics of Construction Production. This program was proposed because the construction industry has developed such that work on the construction site is decreasing and the use of prefabricated parts and components is increasing. The industrialization of construction has resulted in increased logistics costs. The Logistics of Construction Production project has four parts: supervision of the design of the construction project from the logistics viewpoint, development of the logistics on the construction site, purchasing business, and product-related logistics (*8*).

Australia

In Australia robotics research is in its infancy and going through an exploratory and learning phase. In 1989 construction robotics studies at the University of New South Wales (UNSW) in Sydney were begun at the undergraduate and graduate levels. In 1991, the School of Civil Engineering joined with the Schools of Mechanical and Electrical Engineering and Cognitive Sciences as an equal partner in an ambitious robotics and intelligent machines project to develop sensorially complex and problem-solving robots. In March 1992 the first formal construction robotics laboratory in Australia was established in the School of Civil Engineering at UNSW. A variety of strategic research areas is being addressed at the university. These include the following (*9*):

- Robot architecture and configuration research,
- Mechanical engineering aspects of construction robots,
- Sensor technology research,
- Real-time control systems research,
- Artificial intelligence controller research,
- Computer vision research,
- Economic aspects of construction robots research,
- Social aspects of construction robots research, and
- Research into the integration of construction robots with computer-aided design systems.

The following is a list of projects under study at UNSW.

- Robotic arm research with both high-dexterity and high-lift capacity with large reach systems:
  - High-dexterity robotic arms have high-speed precision similar to that of the human arm. With such arms one can perform delicate and complex physical operations such as those required to work on high-voltage power line insulators and to secure nuts and bolts. These arms may be controlled by telerobotic control arms or by a full computer system.
  - Prototype robotic arms have been tested, and a number of large machine forms are under development (*9*).
- Economic and technical feasibility studies are currently being carried out on the following topics:
  - Fully automated vertical slipforming of structures using large capacity and reach on-deck robotic arms,
  - Robotized shotcreting and tunnel lining with general purpose robotic arms,

–Automated steel reinforcement placement and tying,
–Concrete surface finishing with dexterous robotic arms equipped with finishing tools, and
–Automated precast concrete quality control with robotic inspection test stations.

Most of the major universities in Australia have mechatronics or industrial robot teaching and research groups. It is encouraging that Australia has at least begun work in the construction robotics field and has developed a broadly based program in this field (*9*).

Israel

In Israel, research and development at the Technion is directed toward integration and automation of the total delivery process. The National Building Research Institute in Israel involves the interior finishing robot and the automated crane. Interior finishing includes partition building, plastering, and floor finishing. The Israelis are using an expert system for evaluation of the components of a given building design, detailed design, and cost estimate of prefabricated building elements. The expert system is used to generate a list of activities necessary to complete a given building, the resources required to complete the building, and a work progress schedule. In addition, an automated vehicle has been developed by the mechanical engineering faculty at the Technion. The vehicle is able to navigate toward a specified target and omit possible obstacles in its way (*10*).

In addition, to date the Israelis have studied the following aspects of robot-related modules (*10*):

- Performance specification and preliminary design of the robot and its components, including the arm, carriage, sensors, effectors, and control system. The findings are described by Yavani et al. (*11*).
- Adaptation of building technologies to robotic constraints. The main works have included partitions building, plastering, and floor finishing. This study is discussed by Bentur and Puterman (*12*).
- Analysis of optimal configuration in relation to cost, productivity, and operation, as described by Warszawski and Navon (*13*). The computer simulation and measurement of performance of various configuration alternatives have been cited in this study.
- Planning of robotized work with a computerized procedure for the analysis and the feasibility of using robots for different types of buildings is described by Argaman (*14*).
- Testing of physical performance of automated tasks with a small robot (Scorbot of Eshed Robotec, arm reach of 0.60 m and payload of 1.0 kg) adapted to building works. The experiments are described by Argaman and Warszawski (*15*).
- Testing of physical performance of automated tasks with a full-scale robot (with a reach of 1.50 m and payload of 30 kg) adapted to building works. The robot can perform various finishing tasks—painting, plastering, tile setting, partitions, building, and others. It will employ several types of sensors—for avoidance of obstacles, for materials handling, for mapping and navigation, and for identification of openings. The robot is described by Rosenfeld et al. (*16*, *17*).
- Economic analysis of performance involved three applications, which were developed and studied, namely tiling, painting and plastering, and partitions building, and included comparison of robotic versus manual productivity and construction cost. The findings are presented by Rosenfeld et al. (*18*).
- Autonomous control system for the finishing robot employs ultrasonic or laser sensors for mapping of an unknown building environment and artificial intelligence for planning of the work procedures. The progress in this study is detailed by Shohet et al. (*19*).

The scale of research and development research in Israel is quite encouraging. It appears that progress will be made in the areas of excavation, road construction machines, concrete distribution, and the like.

CONCLUSION

The status of automation and robotics is still not at an advanced stage, although the Japanese are advanced in the application of robots in construction. However, important areas of construction still affect human health and safety. Some examples are sand blasting; excavating deep trenches; deep sea work; desert work during sandstorms; mining; some cleaning operations; framing steel high in the air in the cold of winter in such places as Chicago, New York, and Tokyo; and controlling traffic during highway construction, maintenance, and so forth.

Construction work is strenuous and often performed under harsh and hazardous conditions, which require high wages and high insurance rates and often involve large economic losses as a result of work accidents. A robot is capable of working in foul weather, darkness, hazardous areas, and without problems involving motivation and administration, which affect the efficiency of humans. Furthermore, when shortages of skilled labor are a problem, the substitution of robotics for humans has the potential for high productivity, and robots might become more economical to use for a series of simple or repetitive tasks. In the future more advanced research and cooperation among advanced nations are essential for developing more sophisticated automation and robotics in construction.

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Publication of this paper sponsored by Committee on Construction Management.