Automation and Robotics for Road Construction and Maintenance

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Abstract: With rising road construction and maintenance costs and the lack of productivity improvement, automated road construction and maintenance equipment will provide an attractive alternative for the execution of routine work tasks in the future. This paper reviews the typical tasks applicable to this domain, as well as existing and future automated equipment for task execution. The distinction between numerically controlled (NC) machines and autonomous equipment is discussed based on task requirements and machine capabilities. Core technologies for automated equipment are reviewed. Examples of existing numerically controlled equipment are presented. Economic feasibility issues and work safety aspects of automated road construction and maintenance equipment are outlined. The paper concludes that road construction and maintenance tasks have a significant potential for gradual automation due to the repetitiveness and relatively moderate sensory requirements of many tasks. Ultimately, integrated, multitask systems should be feasible once single purpose automated equipment proves successful.

Introduction

Construction productivity on large projects, including road construction, has been constant or declining since the 1970s. This has been coupled with a dramatic increase in construction labor cost and shortage in funding for new road construction and maintenance. At the same time, highway construction costs have been increasing, even after correcting for general inflation (*Statistical* 1986) (see Table 1). These economic factors, as well as the resulting gradual deterioration of the U.S. road infrastructure, motivate the search for improved work productivity. One viable solution is partial or full automation of a number of work tasks. Automation is particularly germane due to the relative simplicity, repetitiveness, and large volume of work involved with roadways. Of course, any investment in automation must consider sound economic analysis of the proposed applications and the financial resources of contractors (Skibniewski 1988a).

In addition to any strictly financial benefits, an expected advantage of automated road construction equipment is improvement in work safety and health. In some instances, laborers will be completely removed from the work loop and thus prevented from being run over by the working machine or other vehicles. In other cases, the health hazards associated with the worker's proximity to carcinogenic materials may be reduced.

Despite this motivation, there is a surprising lack of research and development of partially automated and autonomous road construction and maintenance equipment. At the most recent International Symposium on Robotics in Construction, only two papers referred directly to automation and robotics

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TABLE 1. Highway Construction Cost Indexes 1940–1980 (Commerce 1986)

Year (1)	Gross national product deflator index 1972 × 100 (2)	Standard highway cost index 1972 = 100 (3)	Standard highway cost index construction dollars 1972 = 100 (4)	Percent change cost by decade (5)
1940	29	26	90	
1950	54	48	89	−1
1960	68.7	58	84	−6
1970	91.5	91	99	+18
1980	178.6	255	143	+44

for road construction or maintenance of the 104 presentations (Kobayashi 1988; Herbsman 1988). In contrast, numerous papers concentrated on building construction applications of robotics, which are by nature of work more difficult than applications to road construction and maintenance (Hasegawa 1988). Table 2 illustrates a breakdown of symposium papers by general area. In this table, some related transportation activities are included, such as tunneling work, but very little related to roadway construction. Throughout the world, only a handful of relevant prototypes have been developed, all of which constitute a significant potential for improvement in work productivity, cost efficiency, and hazard reduction. Examples of such prototypes are presented later in this paper.

TABLE 2. Topics of Papers on Construction Robotics at Fifth International Symposium on Robotics in Construction, Tokyo, Japan, June 1988

Topics of presentations (1)	Percentage of presentations (2)
Keynote papers	3
Current status of construction robotics	6
New robotics research directions and administration	5
Design for robotized construction	5
Needs and feasibilities of robotics and construction	4
Robotics in building construction work	15
Research status in construction robotics	4
Mobility and navigation systems	10
Construction management systems	4
Expert systems in construction	7
Robotics for concrete placement and finishing	4
Control systems for construction robotics	9
Robotics for material handling	4
Robotics for earth and foundation work	3
Robotics for building inspection and maintenance	8
Robotics for tunneling work	9
Total	100

TAXONOMY OF WORK TASKS

In order to understand the current developments in road construction automation, a taxonomy of relevant work tasks is useful. In functional terms, road construction involves the following operations, among others:

1. Cut and fill operations: These initial works involve mass transport of earth material within and outside the immediate road construction location to provide the desired sections and profiles of the terrain prior to the commencement of construction. Heavy excavation and off-the-road hauling equipment are typically used for this purpose (Nunnaly 1980).

2. Grading: This task involves the sieving and breakdown of small rock and soil pieces to the desired maximum size, as well as the creation of exact profiles and sections of road at each station. Specialized grading machinery is typically utilized.

3. Base preparation and placement: This work consists of the placement of gravel base on the graded soil. Typical work tasks include gravel dumping, screeding, and compaction. Heavy trucks, screeders, and drums are typically used for this purpose.

4. Surface material placement: This set of construction tasks involves the placement of hot bituminous material, concrete mix, or other surface type, as well as vibration and screeding. Specialized surface-placement equipment is used for this purpose.

5. Curbing and guardrail placement: This work involves the forming and placement of temporary or permanent curbs and guardrails. The tasks include fabrication of curb and guardrail sections as well as their transport and placement.

6. Road maintenance: Maintenance work involves a variety of continuously performed tasks, including snow removal, road painting, grass mowing, brush cleaning, sign placement, pothole and crack filling, and others.

As with other construction activities, labor requirements in road construction are closely associated with the equipment tasks outlined here. They include the operation of excavators and hauling trucks during cut and fill, operation of graders, manual support of road-base placement, curb/guardrail installation, and maintenance tasks.

CATEGORIES OF WORK AUTOMATION

Three major categories of road construction and maintenance equipment exist: mechanized equipment, numerically controlled (NC) hard automation equipment, and semiautonomous/autonomous (flexible, soft automation) equipment. While mechanized equipment has been used on road construction sites for many years, NC equipment constitutes the state of the art utilized in practice, and autonomous equipment is still in the research and development stage.

The major utility of mechanized road construction equipment is its ability to apply large forces over an extended period of time in various work tasks, such as excavation, trenching, and hauling. This capability significantly con

TABLE 3. Examples of Automated Equipment for Road Construction and Maintenance Tasks

Type of task (1)	Equipment Example	
	Numerically-Controlled (NC) (2)	Autonomous (3)
Cut and fill	—	Carnegie Mellon
Grading	—	Spectra-Physics, Agtek
Base preparation and placement	—	—
Surface material placement	Miller formless systems	—
Curbing and guardrail placement	Miller formless systems	—
Road maintenance	Societe Nicolas, Secmar	U.S. Air Force

tributes to task productivity and efficiency in large-volume works. Almost exclusively, this is due to hydraulic force actuation and transmission hardware. This equipment is currently well suited for rough handling in outdoor construction environments due to the lack of, or only minimal, inclusion of naturally fragile electronic devices. Equipment operation requires human support for each executable work task.

Numerically controlled (NC) equipment has the capability of executing repetitive, large-volume tasks with little or no operator assistance. However, the work environment is restricted to the conditions in which only one task or a sequence of identical tasks is required. Also, prior to the execution of work, the removal of any obstacles in the path of the working machine is mandatory. Thus, operator assistance is required when an unexpected obstacle or other operational difficulty is encountered. In some cases, guide wires or light-emitting diodes (LEDs) may be used as established reference points for mobile machines.

Autonomous (robotic) road construction equipment presents the highest level of technical sophistication compared with mechanized and NC equipment. Depending on its level of autonomy, the equipment is capable of partially or fully independent execution of one or a variety of tasks. The operational autonomy of equipment is achieved by the use of sensory data obtained from the environment. The use of sensor data requires subsequent processing and use in the actuation of relevant machine actions. Thus, robotic machines may be capable of acting intelligently in reaction to unforeseen work-site conditions within a limited range of possibilities. If the site conditions become too complex to be recognized and acted upon by the machine, an operator's assistance may also be requested. Also, automatic shutoff of the equipment operation should occur when an unacceptable type of hazard is encountered. This type of equipment can be reprogrammed to suit differing sets of job-site requirements and different types of compatible construction tasks.

Table 3 lists some examples of numerically controlled and autonomous equipment for the types of road construction and maintenance tasks presented here. These examples are briefly described later.

RELEVANT CORE TECHNOLOGIES

The following areas of technology constitute the basis for development of automated road construction and maintenance machines (Hendrickson 1989).

Manipulators
Stationary, articulated manipulator arms are essential components of industrial robotics. The role of a manipulator arm is to move an effector tool into a proper location and orientation relative to a work object. To achieve sufficient dexterity, arms typically require six axes of motion (i.e., six degrees of freedom): three translational motions (right/left, forward/back, up/down) and three rotational (pitch, roll, and yaw). Motion requirements of specific work tasks can be satisfied with various manipulator arm architectures. Movement of manipulator arms requires coordinated drive mechanisms to enable the execution of elementary motions with respect to each axis (or to each degree of freedom). Drive mechanisms used in robotics include hydraulic and air cylinders and electric motors. Special attention is given to precise speed control and extent of all possible motions. Accuracy and repeatability of manipulator motions depend directly on the accuracy and repeatability of the drive mechanism. Drive motions are converted into appropriate speeds and directions of movement by transmission mechanisms.

End Effectors
A variety of end effectors can be employed on robot arms. Typical end-effector tools and devices on automated road construction and maintenance equipment include discharge nozzles, sprayers, scrapers, and sensors. The robot tools are usually modified in comparison with tools used by human workers or even specially designed to accommodate unique characteristics of the working machine. Integration of effectors, sensors, and control devices is possible to accomplish execution of more complex tasks.

Motion Systems
Mobility and locomotion are essential features for road construction and maintenance equipment. A variety of mobile platforms can support stationary manipulator arms for performance of required tasks. An example selection of automatically guided vehicle (AGV) platforms is presented in Skibniewski (1988b). However, most automated tasks supported by AGVs in road construction and maintenance will require modified control systems and larger payloads than those in automated factories.

Electronic Controls
Controllers are hardware units designated to control and coordinate the position and motion of manipulator arms and effectors. A controller is always equipped with manipulator control software enabling an operator to record a sequence of manipulator motions and subsequently to play back these motions a desired number of times. More sophisticated controllers may plan entire sequences of motions and tool activations given a desired work task.

Computer-based controllers work at various levels of abstraction (Goetsch 1988). Actuator-level languages were the first to be developed and to include commands for movements of particular joints in a robot manipulator.

These languages are cumbersome to use since a programmer must specify elementary movements and individual positions for each joint in the manipulator arm. At a higher level of abstraction, manipulator-level or end-effector languages exist. These languages include commands specifying desired movements or positions of the end effector of a robot manipulator. When such a command is issued by an operator, the software must determine what actuator-level commands are required to achieve the desired final position. At the highest level of abstraction are object-level control systems and languages that can plan manipulator movements in response to goal statements or sensor information. Knowledge-based expert systems may be used for this purpose.

Sensors

Sensors convert environmental conditions into electrical signals. An environmental condition might be a mechanical, optical, electrical, acoustic, magnetic, or other physical effect. These effects may occur with various levels of intensity and can be assessed quantitatively by more sophisticated sensors. These measurements are used to control robot movements and, in advanced robots, to plan operations.

Interpreting sensor information for the purpose of manipulator and end-effector control is a difficult and computationally intensive process. Consequently, most existing robots have only limited capabilities to sense the environment. As with control languages, different levels of interpretation exist. At the lowest level, mechanisms for receiving each sensor signal must be implemented, so sensor-level programs are required. Direct sensor measurements are converted into parameters describing the physical effect being considered. Finally, parameter values are integrated into a world model of the robot environment at the object level. Since different interpretation operations are very complex, smart sensors handling the calculation of parameters internally are gaining increasing attention. As a result, the robot controller does not devote time to polling and interpreting direct sensor signals. Since robots require real-time interpretation to guide robot actions, this form of parallel or distributed processing is highly desirable.

Artificial vision is an example of sensor and interpretation complexity. Vision is an information processing task in which two-dimensional arrays of brightness and/or color values received by a camera or other type of sensor are manipulated to form a two- or three-dimensional model of environment. This process may involve inferring the types of objects or material characteristics present in a scene with the use of complicated object-matching procedures.

Integrating sensor information and machine control can be accomplished at various levels of abstraction. At the lowest level, tactile or proximity sensors may be added to a robot to stop the machine during imminent collisions. At higher levels, sensors provide the information required to construct a world model of a robot's surrounding. This world model is subsequently used to plan robot motions to accomplish a desired goal. This overall integration distinguishes cognitive robots that are able to sense the environment, interpret data, plan, and execute work tasks.

Hard Automation (NC) Equipment

The equipment examples described in this section are designed for the execution of repetitive construction and maintenance tasks typically performed on roadways. This equipment requires a substantial amount of site preparation before the intended work tasks can be executed. No sensors are employed on the equipment for site data acquisition. Thus, all equipment control functions requiring judgment based on the external environment data are performed by an operator. The motivation for development of these machines came primarily from the expected economic payoff in high-volume highway works.

Societe Nicolas of France has developed a multipurpose traveling vehicle (MPV) used for a variety of maintenance tasks (Point 1988). It is equipped with an air-cooled 120 HP engine and has an overall length of 5.45 m and width of 2.10 m. The vehicle height is 3.10 m with the wheel base of 3.20 m. The vehicle weight (without tooling) is 6.5 metric tons (maximum 13.5 t with tooling). Maximum working speed is 20 km/h, and the maximum traveling speed is 35 km/h. The fuel tank of 300 L, is intended for week-long vehicle operation without refueling.

The main tooling on the vehicle is intended for mowing grass around roadway curbs. It can cut a width of 2.5 m in two passes. It is claimed that the MPV can save up to 50% on mowing costs compared with traditional mowing equipment. A variable height suspension allows automatic loading and unloading, thus allowing MPV to serve as a fast automatic pallet loading and unloading carrier. Thus, additional tooling or other loads can be carried on the pallets. The cost of the MPV machine is approximately $270,000. Future plans for the MPV include sowing, ditch excavation, road marking and cleaning, surface cutting, brushwood cleaning, and salt dispensing.

Miller Formless Systems Co. has developed four automatic slipform machines, M1000, M7500, M8100, and M9000, for sidewalk curb and gutter construction. All machines are able to pour concrete closer to obstacles than with alternative forming techniques. They can be assembled to order for the construction of bridge parapet walls, monolithic sidewalk, curb, and gutter, barrier walls, and other continuously formed elements commonly used in road construction.

The M1000 machine is suitable for midrange jobs, such as the forming of standard curb and gutter, sidewalks to 4 ft, and culs-de-sac. M7500 is a sidemount-design machine for pouring barrier walls, paved ditch, bridge parapets, bifurcated walls, and other types of light forming. M8100 is a midsize system with a sidemount design combined with straddle paving capabilities. The machine can be extended to 16-ft (5-m) slab widths with added bolt-on expansion sections. The M9000 multidirectional paver is designed for larger-volume construction projects. It can perform an 18-ft (5-m) paving in straddle position, with options available for wider pours, plus a variety of jobs from curbs to irrigation ditches in its sidemount mode.

Proportional control of the grade system implemented in the Miller Formless Systems machines utilizes two grade sensors, two amplifiers, two servo valves, and a cross-sloping feature. The cross-sloping feature consists of one slope pendulum, one amplifier, one servo valve, and one remote handset. The steering control system includes two steering sensors, two amplifiers, two servo valves, and two feedback potentiometers.

All the slipforming machines have the capability of operating in a playback mode while following a preset and precleared path of work. With lower labor requirements than traditional forming techniques, the cost-saving potential on large-volume projects is apparent.

Secmar Co. of France developed a prototype of the integrated surface patcher (ISP) (Point 1988). The unit consists of the following components:

- A 19-t (17,000 kg) carrier with rear-wheel steering.
- A 3-m³ emulsion tank.
- A 4-m³ aggregate container.
- A built-in spreader working from the tipper tailboard (a pneumatic chip spreader with 10 flaps and a 10-nozzle pressurized bar).
- A compaction unit.

The ISP unit has a compressor to pressurize the emulsion tank and operate the chip-spreading flaps. The machine uses a hydraulic system driven by an additional motor to operate its functional modules. The electronic valve controls are operated with power supplied by the vehicle battery.

ISP is used primarily for hot resurfacing repairs, including surface cutting, blowing, and tack coating with emulsion, as well as for repairs requiring continuous treated or nontreated granular materials. The unit is suitable for deep repairs using aggregate/bitumen mix, cement-bound granular materials, and untreated well-graded aggregate, as well as for sealing wearing courses with granulates.

The current design of the ISP allows only carriageway surface sealing. It is thus not well-suited for surface reshaping or pothole filling. It is used only for routine maintenance tasks. In operational terms, ISP is not capable of on-line decision making on how to proceed in case of an irregular crack or other non-predetermined task. However, the automated patching can be started either manually or automatically, depending on existence of the optical readers mounted on the equipment that read the delimiters of the work area, and on the mode of action chosen by the operator. It is claimed that the ISP machine can provide overall cost savings in the amount of 40% with respect to the traditional equipment and methods.

AUTONOMOUS EQUIPMENT

Autonomous road construction and maintenance equipment is largely in the stage of infancy. However, a few successful prototypes integrating manipulator and tool action with sensor information have been developed and implemented in practice.

Spectra-Physics of Dayton, Ohio, developed a microcomputer-controlled, laser-guided grading machine. A laser transmitter creates a plane of light over the job site. Laser light receptors mounted on the equipment measure the height of the blade relative to the laser plane. Data from the receiver are then sent to the microcomputer, which controls the height of the blade through electronically activated valves installed in the machine's hydraulic system. A similar device has been developed by Agtek Co. of California (Paulson 1985). An automated soil-grading process implemented by these machines relieves the operator from having to position and control manually the grading blades, thus increasing the speed and quality of grading, as well as work productivity.

Research is being conducted in autonomous inspection of bridge decks with data provided by ground-penetrating radars. Laboratory prototypes of autonomous nondestructive testing devices have been developed at the Massachusetts Institute of Technology (MIT) and the University of Southampton, Great Britain (Maser 1988).

A rapid runway repair (RRR) equipment system development project is under way at the University of Florida and the U.S. Air Force Tyndale Base. The autonomous performance of rubble removal, crack filling, and nondestructive testing, among other functions, is being designed. An important benefit to the Air Force from implementing such a system will be the removal of humans from a life-threatening work environment in combat situations.

A robotic excavator (REX) prototype has been developed at Carnegie Mellon University (Whittaker 1985). REX uses a sensor-built surface model to plan its digging action and interprets sonar data to build accurate surface and buried object depth maps to model the excavation site. Based on the surface topography and the presence and location of buried obstacles, appropriate trajectories are generated and executed. The manipulator is an elbow-type used for subsea teleoperation and was modified for increased envelope and uncluttered profile. It exhibits a payload of 1,300 N at full extension and over 4,300 N in its optimal lifting configuration. A master arm is provided as an operator interface for manipulator setup and for error recovery. Together, the backhoe and the six-degrees-of-freedom manipulator provide nine degrees of freedom for tool positioning and orientation.

Basic research in fully autonomous road equipment navigation has been under way at Carnegie Mellon University for several years (Thorpe 1988; Dowling 1987). The prototypes of mobile robotics are capable of road following based on the visual information provided by sensory data obtained via television cameras, radar, ultrasound emmiters, light-emmitting diodes (LEDs), and infrared scanners from the immediate environment. The machines are capable of real-time data interpretation through an on-board host computer and subsequent actuation of motion based on the obtained directives and encountered stationary or moving obstacles.

AUTOMATED EQUIPMENT OF FUTURE

Developments in this automated road construction and maintenance equipment will lead to the future expansion of advanced technology in high-volume road works. Several new types of machines will be developed for a variety of tasks.

In cut and fill works, further progress is expected in the autonomy of task performance. Excavators, backhoes, and off-the-road dump trucks will navigate autonomously around construction sites with the use of signals emitted from reference locations and received by location sensors mounted on the equipment. The excavation will be performed with little or no monitoring by an operator thanks to the use of surface modeling and object-detection algorithms executed in real-time by on-board controllers.

In grading works, the dissemination of laser-controlled blade operation will be augmented by autonomous grader navigation around job sites.

In base preparation and placement works, automation of equipment assignments will also play an important role in productivity improvement. The efficient movement of gravel trucks, compacting drums, vibrators, screeders, and other equipment over large work areas will be enhanced with automated work scheduling techniques. The equipment will be able to determine its work area, proceed to the job location, and execute an optimum sequence of operations based on dispositions provided by on-board controllers.

In surface material placement works, equipment autonomy will improve the introduction of autonomous navigation and the use of material property

sensors during placement. Such quantities as thickness of asphalt layers, consistency of mix, and layer profiles will be monitored and corrected automatically with the use of sensor-equipped robotic controllers.

In curbing and guardrail placement works, proliferation of numerically controlled equipment will continue. Standards for dimensions, quality, weight, and placement procedures will be developed for the use of NC equipment.

In road maintenance tasks, a variety of new devices integrating autonomous equipment mobility with smart sensors, including artificial vision, and dextrous manipulator end effectors will be employed.

New capabilities of the existing machines will be created from the advancement of fundamental research in robots technology. Improved sensor designs, more efficient robot controllers, and innovative end effectors will all contribute to redefinition of current equipment work procedures. Entirely new types of equipment that integrate several tasks from across the presented taxonomy may also be developed. This will be possible if the development cost of one machine can be spread over several applications unrelated at present. Thus, a systematic approach to the development of functional modules of robotic machines may prove advantageous.

EVALUATION AND CONCLUSIONS

Road construction and maintenance works have a significant potential for gradual automation of their individual tasks, due to their repetitiveness and relatively moderate sensory requirements in comparison with other construction tasks. Ultimately, integrated multitask road construction and maintenance systems may be feasible, once the single-purpose automated equipment proves successful.

A systematic approach to the development of automated road construction and maintenance equipment, based on a thorough ergonomic and economic analysis of relevant work tasks, will result in determining the most feasible alternatives for equipment operational modes. It is anticipated that numerically controlled (NC) equipment will prove sufficient and successful for a majority of routine, high-volume tasks. Autonomous equipment is desirable for tasks traditionally requiring continuous monitoring of machine work by an operator who customarily can take only a limited number of actions when required to correct task execution.

In the case of numerically controlled (NC) as well as autonomous road construction and maintenance equipment, open-ended functional modules for the execution of elementary work tasks should be developed to avoid the effort and expense of building entirely new hardware for many work tasks with similar operational and control characteristics.

Typically, substantial development and testing cost of new equipment prototypes must be offset by significant savings on labor costs, as well as improvement in work productivity and quality. Automated multipurpose equipment may have a substantial advantage over single-purpose machines due to the potential of spreading the development cost over several applications.

A potential for improved equipment safety will be an important factor in application decision making. Safe execution of road construction and maintenance tasks will not only satisfy the requirements of the regulatory agencies and craft organizations, but will also contribute to the improvement of productivity and quality of work by removing workers from cumbersome, repetitive, and often hazardous environments.

The achievement of the outlined potential depends on a substantial investment in applied construction automation and robots research in the following years. A technology development program would be helpful similar to the one adopted by the Japanese government (Okada 1988). Also, more emphasis should be put on technology transfer efforts to ensure timely dissemination of recent advancements into the road construction and maintenance equipment industry and, subsequently, into the equipment market.

ACKNOWLEDGMENTS

APPENDIX. REFERENCES

Dowling, K., et al. (1987). "NAVLAB: An Autonomous Navigation Testbed." *Technical Report CMU-RI-TR-87-24*, The Robotics Inst., Carnegie Mellon Univ., Pittsburgh, Pa., Nov.

Goetsch, D. L. (1988). *Fundamentals of CIM Technology*, Delmare Publishers, Inc., Albany, N.Y.

Hasegawa, I. (1988). *5th Int. Symp. on Robotics in Constr.*, Japan Industrial Robot Association, Tokyo, Japan.

Hendrickson, C., and Au, T. (1989). *Project management for construction: Fundamental concepts for owners, engineers, architects and builders.* Prentice Hall, Englewood Cliffs, N.J.

Herbsman, Z., and Ellis, R. (1988). "Potential application of robotics in highway construction." *Proc., 5th Int. Symp. on Robotics in Constr.*, Japan Industrial Robot Association, Tokyo, Japan, June, 299–308.

Kobayashi, T., et al. (1988). "Study on a robotic system for pavement cutting work." *Proc., 5th Int. Symp. on Robotics in Constr.*, Japan Industrial Robot Association, Tokyo, Japan, June, 289–298.

Maser, K. (1988). "Automated interpretation for sensing in-situ conditions." *J. Comp. in Civ. Engrg.*, ASCE, 2(3), 215–238.

Nunnaly, S. (1980). *Construction methods and management.* Prentice Hall, Inc., Englewood Cliffs, N.J.

Okada, Y. (1988). "Advanced robot technology project in Japan." *Proc., 5th Int. Symp. on Robotics in Constr.*, Japan Industrial Robot Association, Tokyo, Japan, June, 71–80.

Paulson, B. (1985). "Automation and robotics for construction." *J. Constr. Engrg. and Mgmt.*, ASCE, 111(3), 190–207.

Point, G. (1988). "Two major innovations in current maintenance: The multi-purpose vehicle and the integrated surface patcher." *67th TRB Annual Meeting*, Transp. Res. Board, 29.

Skibniewski, M., and Hendrickson, C. (1988). "Analysis of robotic surface finishing work on construction site." *J. Constr. Engrg. and Mgmt.*, ASCE, 114(1), 53–68.

Skibniewski, M. (1988). *Robotics in civil engineering.* Van Nostrand Reinhold, New York, N.Y.

Statistical abstract of the U.S. (1986). Bureau of Census. U.S. Department of Commerce, Washington, D.C.

Thorpe, C., and Kanade, T. (1988). "1987 year end report for road following at Carnegie Mellon." *Technical Report CMU-RI-TR-88-4*, The Robotics Inst., Carnegie Mellon Univ., Pittsburgh, Pa., Apr.

Whittaker, W., et al. (1985). "First results in automated pipe excavation." *Proc., Second Int. Conf. on Robotics in Constr.*, D. Sangrey, ed., Carnegie Mellon Univ., Pittsburgh, Pa., June.

cessing or with machine intelligence. In this article, the current steps toward that future state are outlined. However, this article also presents less advanced robots (including playback robot examples) where they have found application in the construction domain. In this way, a comprehensive survey of current construction robotics is provided, along with examples indicative of future developments.

CATEGORIZATION OF CONSTRUCTION OPERATIONS

There are a number of different ways to categorize the construction industry. For instance, *building* construction includes commercial, industrial, and residential, and *heavy* construction includes roads, bridges, and dams. However, construction applications share certain basic operations. For example, the basic operations in building construction have been described as follows (3):

Element Placement Operations

1. *Building:* This consists of placing repetitive basic structural elements such as bricks and concrete blocks to obtain a rigid structure or part. At present, it usually involves the use of a binding agent such as mortar or adhesives and is work of a repetitive character, requiring relatively high accuracy and consistency.
2. *Positioning:* This involves placement of (typically) large, heavy components in their service locations. It is presently performed by several laborers using building cranes and requires flexibility of movement and reasonably high accuracy on the part of the laborers as well as supporting machinery.
3. *Connecting:* This is the set of operations needed to achieve joint action between different parts of the structure. It often requires special tools and high work accuracy on the part of laborers.
4. *Inlaying:* This is a type of *building* process (1), but is instead applied to existing structural surfaces. It involves placement of small elements attached to each other on a structural base for the purpose of obtaining a continuous surface.
5. *Sealing:* This is the application of a sealant to the joint edges of structural elements to obtain an uninterrupted and isolating surface.

Surface Treatment Operations

1. *Finishing:* This is a mechanical treatment of raw structural surfaces to obtain surface quality or utility. It is

CONSTRUCTION, ROBOTS IN

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INTRODUCTION

There is widespread interest (1,2) in applying robotics to construction, to bring productivity gains to this large but diffuse industry and to extend construction to environments inaccessible to humans. Conventional factory robots are of limited applicability because the construction environment is not permanently structured or maintained. Construction robots, therefore, confront the challenges of task complexity, robot mobility, obstacle avoidance, domain recognition, large force demands, and more. Prototype models and demonstrations are

Filling Operations

1. *Concreting:* This consists of pouring the concrete mix into previously prepared formwork to create structural volume. It requires strength and endurance on the part of laborers.
2. *Excavating:* This is the act in which the site is brought to a controlled geometry from which construction proceeds.
3. *Backfilling:* This describes replacing the empty space between foundation walls and the ground with soil. It requires transferring large volumes of soil with mechanical pushers and backhoes.

In addition to the above operations, there are other elementary activities necessary to perform a successful construction project. They include, but are not limited to, inspection, testing, and operation control.

SUITABILITY OF THE EXISTING ROBOTIC TECHNOLOGY

Construction operations are generally unique, and commercially available robotic systems are at the present time largely unsuited for such work. The reasons for this are quite complex. They include the need for sturdiness and roughness of equipment at construction sites, which is very different from most manufacturing environments. However, there are numerous other technical problems specific to the nature of an *ill-structured* construction environment, which are largely unsolved at present. Therefore challenges facing construction robotics are greater than those facing robotics in most manufacturing applications. The research problems include:

- *Robot Mobility:* Mobile-based equipment is essential for most on-site construction applications. Mobility requires sophisticated navigational capabilities involving obstacle avoidance, surprise sensors and surprise-handling algorithms, robot vision systems, new control systems and data processing units, and so on.
- *Robot Sensing:* Construction robots will have to use sensors for vision, pattern recognition, and proximity sensing in order to perform in an unstructured environment.
- *Construction Robotic Grippers:* Further development of robotic grippers is needed for broader potential use in construction operations. Emphasis should be put on developing new types of grippers particularly suitable for specific operations.
- *Control Systems:* Available control systems have significant limitations on their ability to modify robot behavior in response to sensed conditions. Also, response time to these conditions is not yet satisfactory to perform most work tasks. Computational capabilities will have to be significantly expanded to handle large amounts of sensory data and to process them in an acceptable amount of time.
- *Robot Accuracy:* In construction work, the design accuracy of robots is likely to be affected by intensive wear. Measures must be taken to assure proper positioning accuracy of a robot for each specific task, possibly by self-calibration procedures. This calls for greater use of *servo control* computations than presently employed in manufacturing robots.
- *Weight of Hardware:* Most existing industrial robotics hardware structures are relatively massive and unwieldy; at maximum they can lift and handle objects representing only about 10% of their own weight. To avoid overloading structures under construction, this proportion must be altered to levels more typical of construction equipment.
- *Hardware Stability Problems:* Most objects to be handled by construction robots are heavier than their counterparts in manufacturing, and the reach of any construction robot arm will be greater than that of a manufacturing robot. Therefore, considerably greater robot flexibility must be anticipated, with possible stability implications.
- *External Factors:* External factors such as weather conditions, extreme temperatures, dust, and excessive vibrations affect most construction environments. Influences referred to in cybernetics as "noises" can significantly affect the level of responsiveness of robot sensors and dampen the precision of manipulator performance. In most of the development efforts, designers of robotic sensors and manipulators must always take these constraints into account, again demanding special control mechanisms for such new applications.

Present robot technology nonetheless offers some capabilities that can be employed in construction applications. Spray robot technology is well developed, and a number of early construction applications have originated with that function. Similarly, certain sensing functions are presently reliable; an example would be a single-channel touch sensor. Again, there exist construction applications that are satisfied with this limited but very accessible technology. Another obvious example is the fundamental capability of a robot to perform repetitive motion, whether programmed algorithmically or taught. This capability suits particular construction applications at the present time and is being exploited where appropriate.

EXISTING PROTOTYPES AND OPERATING MODELS

Although construction robots are in general not commercially marketed, there have been significant attempts to robotize a number of narrow applications, some of which appear to be technically and potentially economically feasible. These attempts have so far covered virtually every major area of construction operations, such as:

- *Surface Finishing:* There are a shotcrete robot by Kajima, a fireproofing spray robot by Shimizu, a slab finishing robot by Kajima, and a wall climbing robot by Nordmed Shipyards.
- *Tunneling:* Robotic-type controls have been introduced in drilling and in shield driving by Kajima.
- *Excavation:* There have been a robotic excavator (REX) demonstration by Carnegie-Mellon and DRAVO, automatic grading control, and a diaphragm wall excavating robot by Kajima.
- *Structural Element Placement:* A reinforcement-placing robot has been developed by Kajima.

• *Construction Inspection:* A core-boring robot and magnetic sensing of concrete reinforcement have been developed by Carnegie-Mellon.

A number of technical and corporate publications describe existing field examples (4–6). These and other examples are now discussed in some detail.

Examples of Robots for Surface Finishing

Shotcrete Robot. In the new Austrian tunneling method, shotcrete application takes as much as 30% of the total time; improving the efficiency of this one task can bring about significant benefits. Normally, a skilled operator is needed to regulate the amount of concrete to be sprayed and the quality of hardening agent to be added, both of which depend on the consistency of the concrete. Kajima Corporation has developed and implemented a computer-controlled applicator (Figure 1) by which high-quality shotcrete placement can be achieved. The special features of this system are the following:

• The concrete is fed and jetted by compressed air.
• The accelerator, a dry powder, is mixed into the concrete at a point approximately 2 m before the mouth of the nozzle.
• The rate of shotcrete application is in the range of 4–6 m^3/h and varies with the consistency of the concrete.

The required air volume and pressure vary with the consistency of the concrete; the appropriate rate of shotcrete application is controlled by computer. As a result, the work can be performed without the presence of an engineer familiar with the characteristics of concrete and applicator equipment.

Three employed types of automated shotcrete nozzle manipulation include remote control, semiautomatic remote control, and robot playback. The equipment described here can be classified as semiautomatic remote control, and the playback type robot was developed by Ohbayashi-Gumi, Ltd. and Kobe Steel,
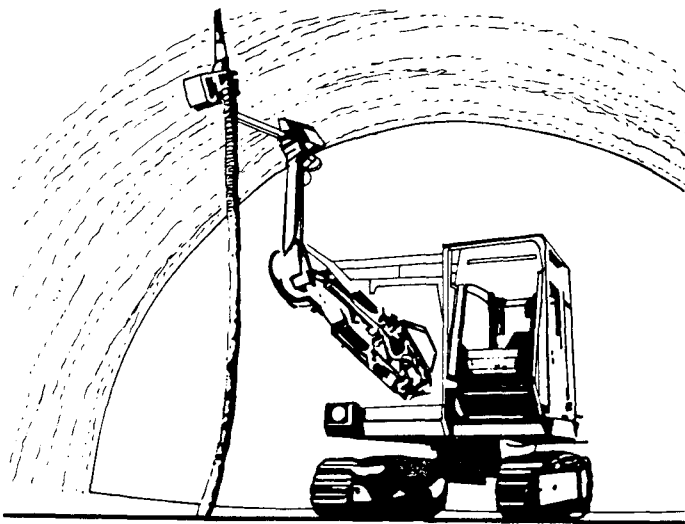

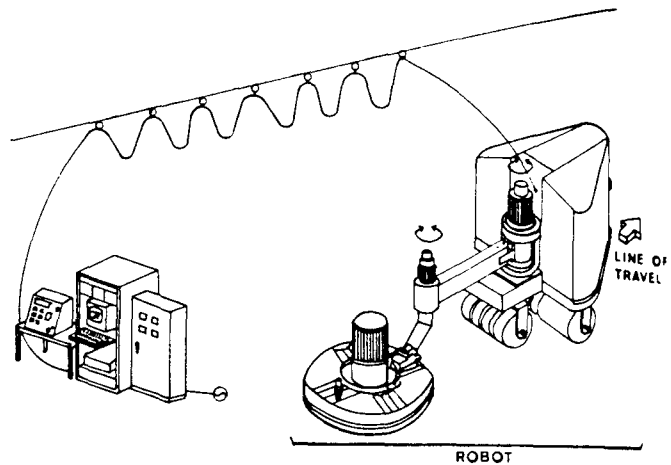**Figure 1.** Kajima shotcrete robot (4). Courtesy of *IABSE Proceedings.*

Figure 2. Kajima slab finishing robot. Courtesy of M. Saito, N. Tanaka, K. Arai, and K. Banno, Mechanical Engineering Development Department, Kajima Corporation.

Ltd. The first unit of this type is now in use on the work site in Japan.

Slab Finishing Robot. Finishing the rough surface of a cast-in-place concrete slab after pouring usually requires laborious human hand work, often performed at night and in adverse weather. The robot designed for this task by Kajima Corporation (Figure 2) is mounted on a computer-controlled mobile platform and equipped with mechanical trowels that produce a smooth, flat surface. By means of a gyrocompass and a linear distance sensor, the machine navigates itself and automatically corrects any deviation from its prescheduled path. It is controlled by a Z80 8-bit microprocessor and is connected by an optical fiber transmission system to a host computer, enabling monitoring of robot position by graphic display.

The entire system consists of a main unit with a mobile platform, a horizontal articulated arm with a rotary trowel, a host computer, a console, and a power supply unit. The operator inputs the course, the starting position coordinates, the number of arm swings, the angle of the trowel and number of trowel rotations, and the degrees of the turns at each corner. Once the robot starts operation, no further instructions are necessary. As the robot advances, it pulls the trowel arm, which swings back and forth. The robot features a gyrocompass to keep the robot from tilting, a rotary encoder to determine distance traveled, and sensors to detect obstacles. This mobile floor finishing robot is able to work to within 1 m of walls. It is designed to replace at least six skilled workers.

Fireproofing Spray Robot. Shimizu Company has developed two robot systems for spraying fireproofing material onto structural steel. The first version, the SSR-1 (Figure 3), was built to use the same materials as in conventional fireproofing, to work sequentially and continuously with human help, to travel and position itself, and to have sufficient safety functions for the protection of human workers and of building components. For the spraying function itself, the KTR-3000 (Kobelco-Trallfa spray robot) was initially employed because of
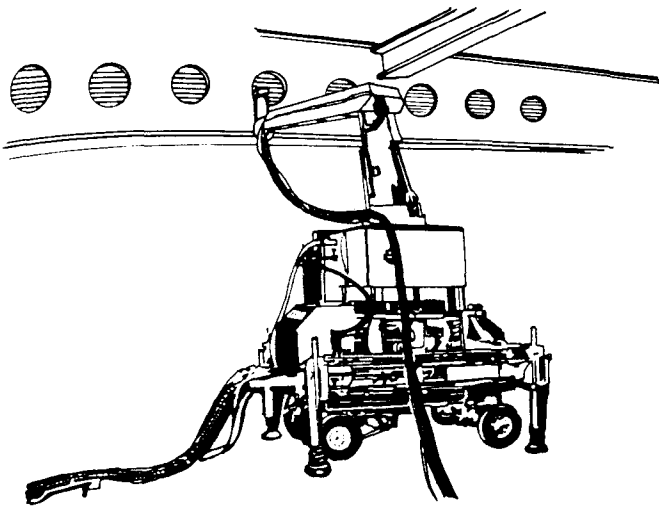
Figure 3. Shimizu fireproofing spray robot (4). Courtesy of *IABSE Proceedings*.

its large memory module capacity, its spray nozzle weight capacity (greater than 3 kg, satisfactory for the fireproofing work), and its use of continuous path (CP) control.

The manipulator consists of four modules: the base, a vertical arm, a horizontal arm, and a wrist. It has six degrees of freedom of motion, which are operated by a playback control system consisting of an electrohydraulic servo control. The height and width of the operating area are approximately 2 m × 3 m. Electric wires, hydraulic hoses, and material-handling hoses are mounted on supports, set at 1 m intervals, which can move smoothly across the floor. The manipulator is mounted on a mobile platform weighing 220 kg, which has four outriggers for stable positioning when spraying. The manipulator is controlled by an independent controller, and the mobile platform follows a wire path and has a sequential controller that controls both the platform and the manipulator. The manipulator control equipment computer robot control (CRC) system has CP/PTP teaching and CP playback control functions.

The work efficiency was evaluated by measuring the spray time per specific area. As a result, it was found that the processing speed was almost twice as fast as that of the conventional manual method. However, new additional tasks were involved: placement of the path wire and hoisting and initial positioning of the robot system. The specific gravity of the rock wool sprayed (a major determinant of the work quality) is nearly the same as that achieved by a human worker. The biggest problem is the thickness dispersion, which is caused by the inability to supply the material uniformly for spraying.

A second robot system, the SSR-2 (Figure 4), was developed to improve some of the job-site functions of the first prototype. The new features included the introduction of a new positioning system defined in relation to the overhead beams being sprayed, self-traveling and tracking of the robot, eliminating the path wire for guiding the robot, and improving the feeder for supplying the rock wool more uniformly.

The SSR-2 manipulator itself is fundamentally similar to that of the SSR-1, and the mobile platform has additional
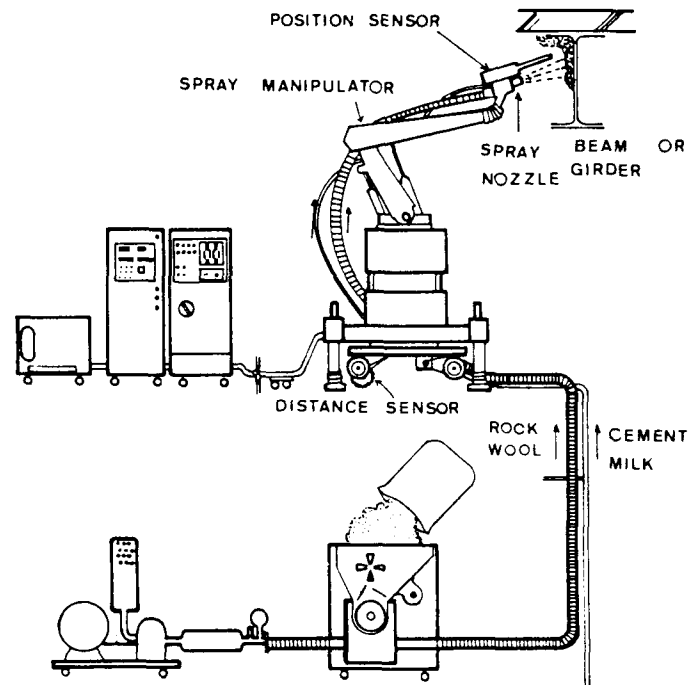

Figure 4. SSR-2 Robot system.

sensors for step counting and obstacle detection. The control system of the SSR-2 has a traveling device controller for path control and for position calculation, based on a 16-bit system (TMS-9995, 16 kbyte ROM, 14 Kbyte RAM). The positioning system of the mobile platform, free of any path wire, is the main improved feature of the SSR-2. As slight elevation deviations exist due to floor unevenness, the SSR-2 must adjust its position through sensor information. The SSR-2 measures its position by touch, by gauging the distance to the web and the bottom of the beam flange above.

From an economic viewpoint, the SSR-2 can spray faster than a human worker, but requires time for transportation and setup. The SSR-2 takes about 22 min for one work unit, whereas a human worker takes about 51 min. The SSR-2 does not require much personnel power for the spraying preparation, only some 2.08 workdays compared to 11.5 for the SSR-1. This shortening of preparation time contributes considerably to the improvement of robot system economic efficiency. As the positional precision of the robot and supply of the rock wool feeder were improved, the irregular dispersion of the sprayed thickness decreased and became nearly equal to that applied by a human worker.

Wall Climbing Robot. Nordmed Shipyards of Dunkerque, France, developed the RM3 robot (Figure 5) for marine applications, including video inspections of ship hulls, γ-ray inspections of structural welds, and high-pressure washing, deburring, painting, shotblasting, and barnacle removal (7). The RM3 weighs 206 lb (93kg) and has three legs, one arm, and two bodies. Magnetic cups on its hydraulic actuated legs allow the RM3 to ascend a vertical steel plate, such as a ship's hull, at a speed of 8.2 ft/min (150 m/h). RM3 has a cleaning rate of 53,800 ft²/d (5000 m²/d) and a 320-ft (98-m) range. Nordmed
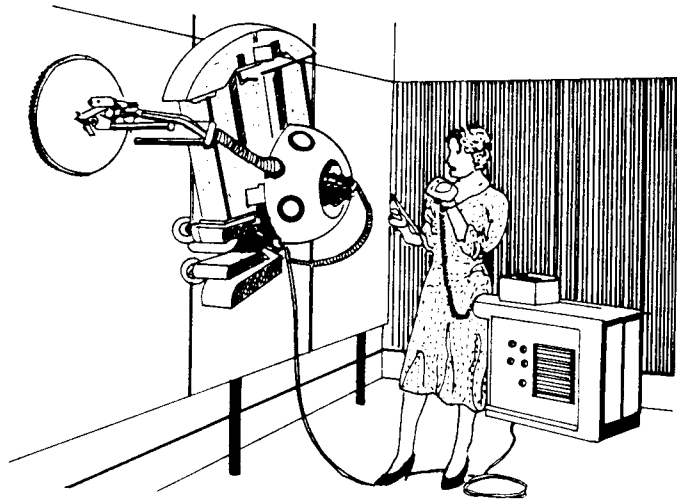
Figure 5. Nordmed Shipyards climbing robot (7). Courtesy of *Robotix*.

entered into a joint venture with Renault to use a version of RM3 to paint chemical storage tanks.

The robot is designed to work without any scaffolding in the following environments:

- Visual inspection for prefabricated blocks.
- X-ray, γ-ray, ultrasonic examination of prefabricated block, and on-board grinding and burr removing.
- Wire brushing before painting.
- High-pressure painting.
- Recycled shot blasting on shell painting joints.

The robot cannot pass obstacles higher than 50 mm and it cannot transfer from one vertical surface to another if the angle formed is greater than 10 deg. However, with suitable modifications, the robot can traverse any steel surface using electromagnetic adhesion pads or flat or curved nonmetal surfaces using suction adhesion pads.

The robot can be operated by remote control or preprogrammed to perform its work automatically. The electrical components of the robot are powered through a low-voltage cable also incorporating an optical fiber link. The intelligence system uses the Texas Instruments Pascal MPP programming language, a high-level language developed for real-time applications using systems designed around TMS 9900 family microprocessors. It is multitask, and its core gives a processing speed performance close to that of an assembler.

An aerospace firm is considering the use of a version of the RM3 robot to paint its aircraft shells and to do its γ- and X-ray testing. Modification for this application would include using vacuum cups to fasten the robot to the aircraft skin. Other potential uses include cleaning or washing the sides of buildings, applying ground coatings, brushing or spraying in radioactive environments inside nuclear power plants, carrying and handling objects in radioactive environments, milling, machining, cutting, and welding in various areas of the construction industry.

Examples of Robots for Tunneling

Five-Boom Drilling Robot. Robot drilling machines of both playback type and numerical control type have been developed and implemented. Kajima Corporation has adopted the playback system and implemented a machine with up to five booms (Figure 6). This fully automated excavating machine is a major
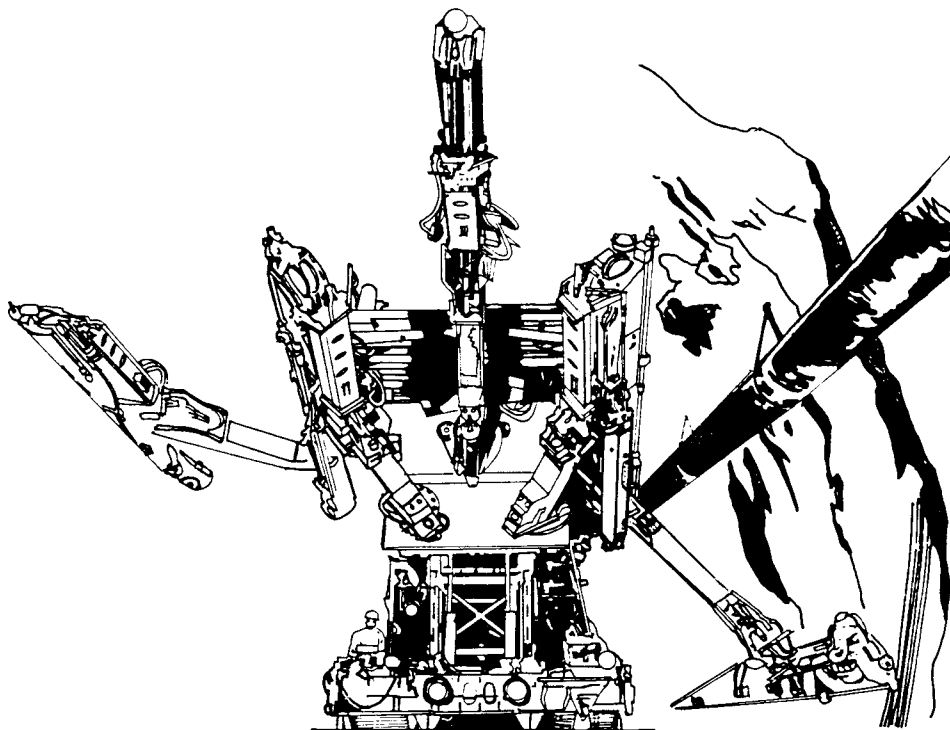

Figure 6. Kajima tunnel drilling robot (4). Courtesy of *IABSE Proceedings*.

contribution to semiautomated technology in tunneling works and makes it possible to execute a series of drilling, blasting, mucking, and shotcreting operations simultaneously on both the upper and lower halves of a tunnel bore. By setting this machine in the basic position for the face to be drilled and starting the automatic drilling device, the machine automatically drills the face in accordance with a previously memorized drilling pattern.

Adopting an automatic drilling machine has the following advantages over previous methods:

- Skilled drillers are not required.
- One person can operate more than one machine.
- Drilling can continue even during the operator's rest period.
- A correct drilling pattern and depth of holes can be secured.
- The drilling time is shortened.
- Workers are liberated from the environment.

Shield Driving. Shield driving is employed in the construction of most tunnels in Japanese urban areas. In shield driving, there would be value in automation and robotization of operations at each step: driving control, removal of excavated material, shield attitude–position control, backfill grouting, segment erection, and handling of materials. Shield equipment manufacturers and general contractors are all performing technical development aimed at final objectives of automating and robotizing all steps of operations. Kajima has developed a system for driving control and attitude–position control. In the operation of slurry shields (being one type of mechanical excavation shield), driving is accompanied by the monitoring of data, including the pressure within the face chamber, the revolving cutter torque, the volume of excavated material, and the properties of the slurry. These data are measured separately in conventional tunneling, and the development of corrective measures arises through the judgment of experienced engineers and skilled operators. However, the relationships between the various data items are not necessarily clear, and much reliance is placed on intuition. With the Kajima system, a determination is made by gathering and analyzing data in real time. With this system, it is possible to attain and maintain a stable driving condition by statistically analyzing the various data obtained in the initial stage of driving and repeatedly feeding these back into the shield operation.

Attitude control is also of great importance in shield driving. The general practice has been to survey line and grade by hand at 5–10 m intervals and correct the direction of the shield in accordance with analysis of survey data. However, the shield would go off-line, and the construction period and cost would be adversely affected by major directional corrections and by weakening of the surrounding ground resulting in ground settlement. In the robotic system, it is possible to monitor continuously the deviation of the shield from the planned line by direction angle, lateral distance, vertical distance, and pitch angle. Because the driving jacks can be controlled from the amount of deviation, the attitude and position of the shield can be controlled in real time; at the same time, the survey operation is eliminated and further major labor

saving becomes possible. At the present time, jack operation based on the measured data has not been automated, but technical development is in progress to link these in the near future.

Examples of Robots for Excavation

REX. Carnegie-Mellon University has developed a robotic excavator (REX) to unearth buried utility piping by mapping an excavation site, planning the digging operations, and controlling excavation equipment. Explosive gases are sometimes ignited accidentally during blind digging of gas utilities, and REX reduces the human injuries and property losses attributed to such explosives; it also has the potential to decrease costs and increase productivity for utility excavation. The REX currently uses a sensor-built surface model to plan its digging action. REX interprets sonar data to build accurate surface and object depth maps to model the excavation site. Based on the surface topography and the presence and location of target pipes, appropriate trajectories are generated and executed. The benign end tooling developed for REX is a supersonic air-jet cutter; this air-jet cutter can dislodge material without the direct contact encountered with bucket excavation. Results to date have been promising (8), and an unmanned, benign excavation in a simulated laboratory excavation has been demonstrated. The research is currently implementing a distributed control architecture for increased speed and efficiency.

Ultradeep Diaphragm Wall Excavator. In the construction of in-ground LNG storage tanks of 100,000 kL or larger capacity in soft reclaimed coastal land, an ultradeep diaphragm wall is constructed. This wall typically descends to an impermeable layer to surround the tank and prevent the inflow of groundwater. In order to make this diaphragm wall effective in shutting out the groundwater, it is important to secure precision in vertical excavation by the diaphragm wall excavator. In an attempt to solve this problem, an automatic excavation system was developed by Kajima Corporation. By controlling the attitude of the machine during excavation, and by controlling the load in accordance with the physical properties of the soil being excavated, it has been possible to secure an excavation precision of over 1/1000.

Automatic Grading Control. A limited but significant example of robotics is now widely used in excavation operations in the San Francisco bay area (9). Excavation operations such as grading (scraping) and trenching (for subsurface drains and utility lines) are a major part of site preparation. A critical element in such work is the control of the invert elevation to which the excavation is performed. Conventionally, this has been done manually using levels or string lines, creating a tedious and discontinuous operation.

An automation mechanism was developed that is presented here as an intelligent robotic example. It can be defined as intelligent because it senses, thinks, and acts. It is a single-channel control that automatically scrapes or grades to the specified invert elevation. It consists of a laser level plane, a sensor mounted on the excavator blade, and a microprocessor

that servos blade position to the specified invert elevation. The operator is left to drive the machine, and blade control is handled automatically and smoothly. In addition to decreasing labor demand, higher machine speeds are possible, as is improved efficiency from the continuity of the operation.

This example differs from most of the others in that it is a single-channel robot, but one which nonetheless contributes highly to productivity. Its simplicity and robustness have made it an example of robot technology that has entered the marketplace. It is supported not by advanced corporate technology, but instead by local application skills using modern products such as laser levels and microprocessors.

Examples of Robots for Assembly

Reinforcement Placing Robot. A robotic adaption for reinforcement placing was developed by Kajima Corporation (Figure 7). It carries up to 20 reinforcement bars, automatically placing them in floor slabs and walls according to a variety of preselected patterns. On many construction projects, rebars for such applications often have diameters in the range of 33 mm, are 8 m long, and weigh more than 100 kg, requiring considerable labor to position. According to the company, this robot has achieved 40–50% savings in labor and 10% savings in time on a number of projects (such as nuclear power plants) requiring heavily reinforced foundations.

Examples of Robots for Inspection

Robotized Core Boring. Carnegie-Mellon University developed a rover in use in the radioactively contaminated areas at the Three Mile Island (TMI) nuclear power plant in Pennsylvania. As a recent robotic tooling (Figure 8), a device was developed to recover drilled concrete core samples. In this application, they are recovered to provide samples of contamination and its characterization with depth from the surface. However, the broader problems of concrete coring and of concrete or rock drilling are pertinent to construction robotics. The tooling employs robotized drilling modules. In the present application, the vehicle positioning remains a teleoperated function with televised feedback. The application demonstrates the pertinence of robotic technology at one level in the system, teleoperation at others, and pure mechanical design at others (10).
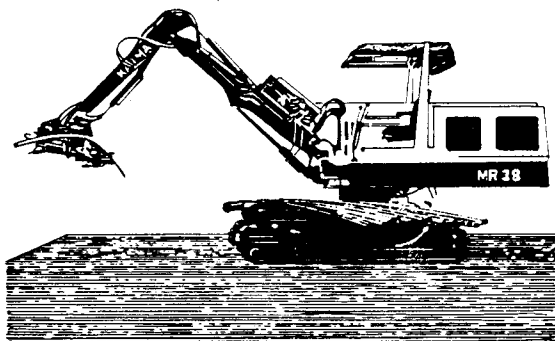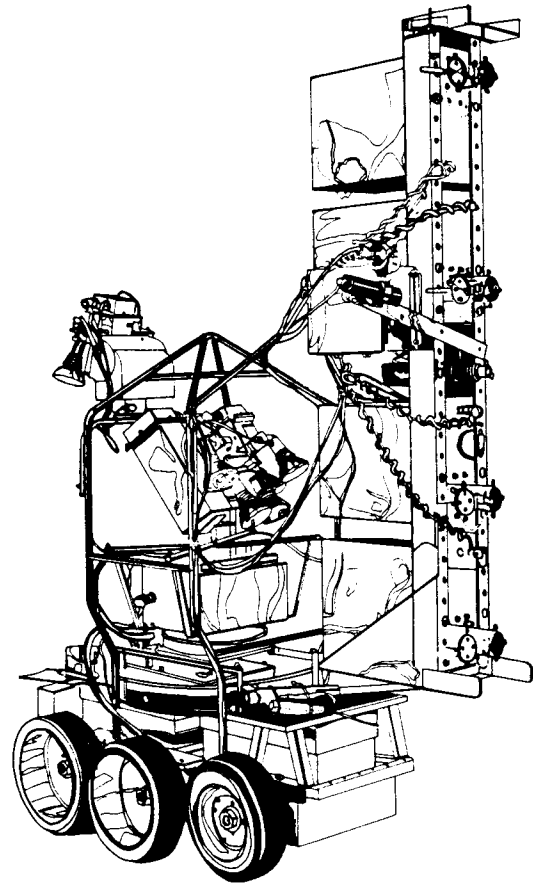

Figure 8. Carnegie-Mellon remote core-boring tooling on TMI rover. Courtesy of Construction Robotics Laboratory, Carnegie-Mellon University.

Magnetic Sensing with a Robot. Carnegie-Mellon University developed an intelligent magnetic sensor to automatically scan, size, and map embedded steel such as reinforcing bars in concrete and pipes in the ground. The mapping of embedded concrete reinforcing is useful to validate as-built structures, and the mapping of buried pipes is important in the excavation of utility lines. In the prototype, a robotic scanner moves a magnetic sensor in a rectangular area, and the output is digitized to form magnetic images (11). Low-level processing extracts features from the data; a postprocess compares data features to a template library of ferrous object patterns and predicted anomalies that result from an idealized ferrous source. Future efforts are to integrate an expert system to guide deductions, verify solutions, and control strategy.

Tile Inspection Robot. Kajima Corporation has developed a tile inspection robot (Figure 9). The traditional method consists of manually tapping each individual tile with a hammer and judging its adhesion by the sound produced. The robot inspects wall tiles automatically; a microprocessor-based system in the ground console analyzes the sound that a robotic tapping head produces. The adherence strength and location of each tile are automatically recorded.

Figure 7. Kajima reinforcing bar placement robot (4). Courtesy of *IABSE Proceedings.*

Figure 9. Kajima tile inspection robot (4). Courtesy of *IABSE Proceedings.*

SYSTEMS OF THE FUTURE

The Near Future

Research and development continues for other construction applications for which no prototype device can be cited. However, such studies are likely to reach some level of field demonstration in the near future. Therefore, two representative applications are presented.

Building Construction and Prefabrication. Building construction often draws upon prefabricated components or assemblies. Producers, builders, and researchers have begun the study of systems to robotize the construction process or key portions thereof. One example is in concrete block placement, for which laboratory small-scale demonstrations have been performed at Carnegie-Mellon University and elsewhere. In those studies, a robot was able to build a sample block wall to a design database containing door and window openings. Studies included examples with random block size. The robot would measure the block and then process a task plan based upon that information, working at all times toward the design geometry. It is important also to recognize that when robotization proceeds, the block will evolve from the present one (constrained to be handled by humans) to blocks of larger size. This will lead to changes in block characteristics, such as the use of reinforcement or mechanical interlock, which cannot be accommodated at present. Therefore, a new material type will be put into service, with the promise of greater efficiency.

Prefabricated building panels or modules are an advanced technology in many countries. The advantages of mechanization and automation are recognized by the proponents of that technology, and their interest logically extends to automation of tasks after the component leaves the factory. Studies of robot technology have been started, and some level of demonstration should be expected in the near future.

Earth Structures. The building of dams and embankments represents the forming of an earth structure to an intended large-scale geometry. The elemental acts of deposition or removal are repeated in a long and largely repetitive pattern. Robotization of these elemental tasks will permit continuous execution of such an accretion process. Moreover, the robot devices will operate under the control of a central computer environment combining the design information, the monitored field information, the task management, and the project database. This type of application shares the characteristics of surface mining, and it is likely that developments will propel both of these major application areas together.

The Far Future

The far future will feature exploitation of domains such as the subsurface and outer space. The act of exploiting such domains will require some ordering of that environment or some type of construction. It is noteworthy that conventional construction exposes robotics to the challenges of an uncontrolled environment, and that those challenges reappear in this long-term perspective on the role of robots.

An important element of the future is the expanded role to be filled by the computer. An integrated computer environment (12) is envisioned to support a project through numerous stages including:

- Conceptual design.
- Detailed design.
- Fabrication.
- Materials handling and site management.
- Erection and construction.
- Construction management.
- Operation.
- Maintenance and repair.
- Decommissioning.

Such an integrated computer environment is an ultimate objective for a more perfect engineering of constructed facilities. The robot system is needed to make such a model complete. Note that some portion of this total scope is reflected in the earth structure application cited earlier.

RESEARCH FRONTIERS

Research problems were identified earlier when addressing the suitability of existing robot technology. It is clear that construction robotics will advance with new results in many areas including:

- Robot mobility.
- Vision and pattern recognition.
- Navigation and positioning.
- Sensing and sensor-based control.
- Dynamics and control.
- Obstacle detection and avoidance.

- Hierarchical control and planning.
- Knowledge-based expert systems.

In some cases, researchers in construction robotics are major contributors to these more general research areas, and in others the lead role originates elsewhere. In any event, the reader is referred to the appropriate articles on those and many other topics.

There are research frontiers in construction robotics, important to other applications, which may not yet be widely known. One is the problem of domain modeling, constituting the development of a computer model of an environment in which robots move and work, interacting with domain objects both physically and functionally. Researchers (13) are developing a domain model for robotic construction and maintenance in facilities such as power plants. An object-oriented programming language is employed, and all entries are treated as objects in that sense. Another example, originating in construction robotics but pertinent to many applications within and without robotics, is the representation and manipulation of geometric information in knowledge-based expert systems. Construction robotics is an application drawing heavily on expert systems and at the same time dealing with physical objects. Previous attempts to operate on geometric information have been tedious and incomplete. Research proceeds at Carnegie-Mellon University for a more fundamental geometric modeling system, one designed to support expert system applications. Similarly, work proceeds on the application of expert systems to the control of heavy equipment such as mining machines; this is another example of research directions common to construction and other application areas. A summary statement of research frontiers raised by construction robotics is generated by the broad, complex system nature of the problem. An autonomous robot system will feature decision capabilities at the reflexive, tactical, and strategic levels. It will be cognitive in spatial terms and in force terms. It will engage issues of perception, representation, abstraction, and modeling. Although the present examples of construction robots may be limited in number and scope, autonomous construction as a research area is a crucible for some of the most far-reaching problems in robotics.

BIBLIOGRAPHY

1. *First International Conference on Robotics in Construction,* Department of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pa., 1984.

2. *Second International Conference on Robotics in Construction,* Department of Civil Engineering, Carnegie-Mellon University, Pittsburgh, Pa., 1985.

3. A. Warszawski, "Application of Robotics to Building Construction," Carnegie-Mellon University, Pittsburgh, Pa., Tech. Rep., 1984.

4. Y. Sagawa and Y. Nakahara, "Robots for the Japanese Construction Industry," *IABSE Proceedings* 7, (P-86/85), (May 1985).

5. T. Yoshida and T. Ueno, "Development of a Spray Robot for Fireproof Treatment," *Shimizu Technical Research Bulletin* (4), (Mar. 1985).

6. S. Suzuki, "Construction Robotics in Japan," presented at the *Third International Conference on Tall Buildings,* Chicago, Ill., 1986.

7. "Robot Climbs the Walls," Editorial, *Robotix News,* (1, 6 July/Aug 1985).

8. W. Whittaker and co-workers, "First Results in Automated Pipe Excavation," presented at the *Second International Conference on Robotics in Construction,* Carnegie-Mellon University, Pittsburgh, Pa., June 1985.

9. B. Paulson, "Automation and Robotics for Construction," *ASCE Journal of Construction Engineering and Management* 111 (3), 190–205, (Sept. 1985).

10. W. Whittaker and co-workers, "Three Remote Systems for TMI-2 Basement Recovery," presented at the *ANS Meeting on Remote Technology at TMI,* San Francisco, Calif., 1986.

11. B. Motazed, *"Inference of Ferrous Cylinders from Magnetic Fields,"* Ph.D. dissertation, Carnegie-Mellon University, Pittsburgh, Pa., Dec. 1984.

12. S. Fenves and D. Rehak, "Role of Expert Systems in Construction Robotics," presented at the *First International Conference on Robotics in Construction,* Carnegie-Mellon University, Pittsburgh, Pa., June 1984.

13. W. Keirouz, D. Rehak, and I. Oppenheim, "Object-Oriented Domain Modeling of Constructed Facilities for Robotic Operations," presented at the *First International Conference on Applications of Artificial Intelligence to Engineering Problems,* Southhampton University U.K., Apr. 1986.

General References

Y. Hasegawa, "Robotization of Reinforced Concrete Building Construction," presented at the *II International Symposium on Industrial Robots,* Tokyo, Japan, 1981.

J. S. Albus, A. J. Barbera, and M. L. Fitzgerald, "Programming a Hierarchical Robot Control System," *Proceedings of the 12th International Symposium on Industrial Robots,* Paris, France, 1982.

Y. Hasegawa, "Robotization of Building Construction Part 1," *Robot* (33), (1982).

Y. Hasegawa, "Robotization of Building Construction Part 2," *Robot* (34), (1982).

T. Pavlidis, *Algorithms for Graphics and Image Processing,* Computer Science Press, Rockville, Md., 1982.

T. Furukawa and S. Kikukawa, "Introduction of Robots to the Construction Work Site," *Robot* (38), (1983).

K. Goto and co-workers, "Self-Climbing Inspection Machine for External Wall," *Robot* (38), (1983).

Y. Hasegawa, "Robotization of Construction Work," *Robot* (38), (1983).

S. Matsubara, "Floor Cleaning Robot," *Robot* (38), (1983).

P. Sjolund and M. Donath, "Robot Task Planning: Programming Using Interactive Computer Graphics," presented at the *Robots 7 Conference,* Chicago, Ill., 1983.

D. Sriram and co-workers, "Potential for Robotics and Artificial Intelligence in Tunnel Boring Machines," Robotics Institute, Civil Engineering and Construction Robotics Laboratories, Carnegie-Mellon University, Pittsburgh, Pa., Tech. Rep., Jan. 1983.

J. Crowley, "Dynamic World Modeling for an Intelligent Mobile Robot Using an Ultra-Sonic Ranging Device," Robotics Institute, Carnegie-Mellon University, Pittsburgh, Pa., Tech. Rep. 84–27, 1984.

B. Yamada, "Development of Robots for General Construction and Related Problems," presented at the *Research Conference,* Material and Construction Committee, Architectural Institute of Japan, Oct. 1984.

G. Agin and co-workers, "Three Dimensional Sensing and Interpretation," Robotics Institute, Carnegie-Mellon University, Pittsburgh, Pa., Tech. Rep. 85–1, 1985.

M. Skibniewski and C. Hendrickson, "Evaluation Method for Robotics Implementation: Application to Concrete Form Cleaning," presented at the *Second International Conference on Robotics in Construction,* Carnegie-Mellon University, Pittsburgh, Pa., June 1985.

M. L. Maher, I. J. Oppenheim, and D. R. Rehak, "Computer Developments for Mining Robotics," presented at the *Second International Conference on Robotics in Construction,* Carnegie-Mellon University, Pittsburgh, Pa., June 1985.

W. L. Whittaker, J. Crowley, I. J. Oppenheim, and co-workers, "Mine Mapping by a Robot with Acoustic Sensors," presented at the *Second International Conference on Robotics in Construction,* Carnegie-Mellon University, Pittsburgh, Pa., June 1985.

M. P. Rosick, "Obstacle Avoidance for a Mobile Manipulator," Master's thesis, Carnegie-Mellon University, Pittsburgh, Pa., Sept. 1985.

A. Warszawski and D. Sangrey, "Robotics in Building Construction," *ASCE Journal of Construction Engineering and Management* **111** (3), (Sept. 1985).