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)	Equipment Example: 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 lanaguages 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-m^3 emulsion tank.
- A 4-m^3 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.

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