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ROBOTIZATION OF ROAD CONSTRUCTION: CURRENT TECHNOLOGIES AND ECONOMIC ANALYSIS

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ABSTRACT

Recent advances in the development of automation technologies suitable for use in road construction and maintenance provide opportunities to improve work productivity and quality, to reduce labor costs, to decrease worker exposure to road hazards, to minimize impeding traffic, and to comply with current environmental regulations. The purpose of this paper is to provide an overview of the state-of-the-art in the robotization of road construction and maintenance operations. Specific robot hardware and software technologies currently available or in developmental stages are described. The findings from an economic evaluation of developing and/or implementing such technologies are presented. The benefits and limitations of using robots over traditional equipments are discussed. .

1. INTRODUCTION

For the United States to maintain its international competitiveness as one of the leading industrialized nations and to provide adequate services for its people, we must invest in the future by rebuilding our infrastructure. This will involve repairing the infrastructure where it can be repaired and then building new infrastructure as necessary. An increased emphasis must be placed on finding innovative ways of financing infrastructure maintenance and investment, of developing better tools to aid in decision making in regard to infrastructure repair and replacement alternatives, and of performing quality and cost efficient construction which will extend the useful life of infrastructure elements. There is a great potential for improving infrastructure construction through robotization of heavy and highway operations associated with both new road construction and road maintenance. An on-going research project is focusing on applications of state-of-the-art robot hardware and software technologies in highway construction and maintenance (e.g., sensors, end effectors, manipulators, sensor interpretation algorithms, etc.). Additionally, information was gathered on robot hardware and software technologies in the developmental and prototype stages to provide a current and comprehensive review of existing robot technologies. The economics (costs and benefits) associated with the development and use of robots in road construction and maintenance are being evaluated.

2. ROBOTIC SYSTEMS AND RELEVANT TECHNOLOGIES

A typical robotized machines for road construction and maintenance consist of the three basic systems: (1) motion system; (2) control system, and (3) sensory system.

2.1 Motion system

Mobility and navigation are major features in most road construction and maintenance equipment. The Automatically Guided Vehicle (AGV) is one type of mobile robot. It is operated by following a path of inductive wire buried just under the surface of the ground using an electromagnetic sensor system which detects the wire. Another advanced type of mobile robot is the autonomous mobile robot. In contrast to AGVs, Autonomous robots are being developed to be able to be used in a natural uncontrolled environment. They may be equipped by wheels, tracks, or walking legs. Walking robots have the advantage of dealing with a variety of terrain and obstacles. However, coordinating the motion of legs and keeping the balance of the robot are additional designing problems. Generally, to accomplish autonomous navigation the robot would need to be able to perform some basic functions as image processing and analysis, path planning, and obstacle avoidance. These functions can be accomplished by using advanced sensory systems (i.e. vision system and laser, optical, or sonar guidance systems), and intelligent control systems (i.e. knowledge-base system or artificial neural network).

2.2 Control system

The role of the control system is to plan, activate, guide, monitor, and modify the performance of the motion system, i.e. locomotion, manipulator, and end effector, based on signals received from sensors and according to the robot program.
Robotic controllers can be classified into the following levels:

- Limited-sequence control systems are at the lowest level of control. They do not have a feedback system to indicate that a desired position has been achieved. With this method of control the individual joints of the manipulator and end effector can only be moved to their extreme limits of travel via limit switches or mechanical stops. Applications for this system generally involve simple motions, such as pick-and-place operations.

- Play back systems are at a higher level of control. They are either point-to-point or continuous-path control systems. In both systems a series of positions or motions are preprogrammed and then repeated by the robot. In point-to-point control systems, the robot is controlled to move from one point to another in the proper sequence but there is no control on the path taken. Applications include loading and unloading activities and spot welding. In the case of continuous-path control, the path followed by the robot is controlled as well. Straight line motion is a common form, but some robots have the capability to follow a preprogrammed smooth curved path. Applications include arc welding, pavement crack sealing, and painting.

- At the highest level of control are object-level control systems. At this level robots not only have the capability to play back a preprogrammed work cycle, but they can make logical decisions and alter their programmed cycle based on sensor data collected from the surrounding environment. For autonomous mobile robot systems there is a need to process the collected data on a real-time base. Currently, high-level knowledge-base and logic programming systems are increasingly being used for planning and controlling intelligent robots. Artificial neural network and parallel processing systems are being under research for future applications in robotics because they have a control structure that allows a fast brain-like data processing.

2.3 Sensory System

Sensors are used as integral components of the robot's position feedback control system. They are also used to acquire data from the surrounding environment needed by the robot to perform its tasks. A sensor converts one type of external physical effects (i.e. force, temperature, sound, image, etc.) into electrical signals and measures that physical effect after calibrating the sensors. Sensors can be classified into two main groups; tactile and non-tactile sensors.

- Tactile sensors are used to detect contact and in some types, magnitude of contact force between objects and end effectors. They are also applied in sensitive multifinger end effectors and in adaptable feet of walking machines. Strain gages, microswitches, electrical contact switches, and limit switches are examples of tactile sensors. A more advanced form of tactile sensors is the tactile array sensor which is a special type of force sensor. This sensor can identify the shape, contour, and orientation of an object. It is composed of a matrix of force sensing elements combined with pattern recognition techniques. One of the research challenges is developing a computer control algrothim that could combine sensor input data into a coherent picture. In turn, the robot would be able to plan and carry out the appropriate motions needed to identify an object by touch. Cutting, digging, scooping, and compaction are common work tasks for roadway construction and maintenance. For these tasks it is common to use tactile sensors to apply the right amount of force and torque on materials and tools.

- Nontactile sensor applications in roadway construction and maintenance automated equipment can be classified into two main categories; proximity sensors and vision sensors. These sensors can be used for quality control and inspection of material and structures, detection of any surface variation (i.e. holes, edges, etc.), and navigation for mobile robots. For a robot vision system, a camera is needed to supply images of the scene. The camera is often a CCD type, Change-Coupled Device, which uses a light-sensitive computer chips instead of regular films. The image viewed by the camera is digitized and stored in the computer memory. The digital image (called a frame) consists of a matrix of data representing projections of the scene viewed by the camera. The matrix for each frame is then subjected to image processing and analysis for data reduction and interpretation. To accomplish image processing and analysis, the vision system should be programmed with known objects and stored as a computer model to be compared later with the digital images of unknown objects. Current applications of vision sensors and image processing techniques include inspection of roadway pavement surfaces (Sidney 1993), robotic pavement crack sealing system (Haas 1992), and autonomous navigation mobile robots.

3. AUTOMATED EQUIPMENT RESEARCH AND DEVELOPMENT IN ROAD CONSTRUCTION AND MAINTENANCE

Roadway construction and maintenance represents a considerable potential for applying robotics technology. The repetitive nature, the unsafe conditions, the continuous increase in labor costs, and the increasing traffic volume are some good reasons for the robotization of road construction. Another reason is that many of the road construction equipment have mechanism and hardware similar to those of robotics. Here the main operations within road construction and maintenance are described and followed by the state-of-the-art research and development.

3.1. Earthwork-Related Operations

These operations involve topographic surveying to calculate cut and fill quantities and mass transport of earth material to and from the work site to establish a desired profile. Grading work to establish line and grade is followed. Activities involved include surveying, excavation, loading, hauling, and dumping earth material, and rough and fine grading. Examples of recent automated systems are:

- In recent years the Global Positioning System **(GPS)**, a surveying system that takes advantage of artificial satellites, has attracted attention. An automated system for earthwork measurements using the Global Positioning System has been developed at the Technical Research Institute of Fujita corporation in Japan. The system utilizes a device to automatically hold an antenna level mounted vehicle, and linkage computer program for the transformation of coordinates obtained by GPS surveying to the ordinary plane coordinates (Okano 1993).

- A similar surveying system has been developed by the Construction Technology Development Dept. at Taisei Corporation in Japan. This system **(Survey Robot)** is able to measure the three dimensional coordinates at 0.5 second while a remote-controlled vehicle with a GPS receiving antenna is running. This automated system has accomplished the three-dimensional topographic survey at 4,000 points in an area of 20 hectare in two hours (Kanzaki 1993).

- Mobility and locomotion on unstructured natural ground are essential functions for a roadway construction equipment. For robots that perform earthmoving and off-road hauling activities, tracks and/or walking legs are better suited for dealing with rough terrain and obstacles. A walking teleoperated machine has been developed by Helsinki University in Finland, called **MECANT**. The machine is capable of moving in rough terrain and stabilizing under different loads.

- Basic research is being conducted as a part of a national research and development program in Japan on autonomous underground excavation walking robots. This robot consists of three system components; a manipulation system with parallel link manipulator, a locomotion system consists of a mobile platform supported by a pair of crawlers and four legs, and a task planning system utilizes tactile sensor data and a cutting model of the soil (Homma 1993).

- An intelligent autonomous robot excavator called **LUCIE** (Lancaster University Computerized Intelligent Excavator), has been developed by a multidiciplinary team at Lancaster University in the UK. LUCIE uses digital optical encoders to know the position and inclination of the excavator bucket. A tilt sensor is also used to guard the excavator against tipping. A high-level rule-based system based on an artificial intelligence technique known as a production system, provides the source of intelligence for this robot (Seward 1992).

- Another Robotic EXcavator **(REX)** has been developed at Carnegie Mellon University in the USA. Using sonar sensors and a sensor-built surface model, REX is able to recognize the surface topography and the location of buried objects and plan its digging trajectories (Skibniewski 1988).

- Research is currently being conducted on robotic excavation focusing on obstacle detection, recognition, and mapping. A laboratory prototype of a robotic backhoe excavator has been developed at North Carolina State University in the USA. This robotic excavator is able to detect obstacles during digging and map their surface contours. It is also able to discriminate between utility lines and removable obstacles using "multiple sensors such as a load cell, accelerometers, and angle encoders" (Huang & Bernold 1993).

- An autonomous dump truck system is currently under development by Hazama Corporation and the University of Tsukuba in Japan. A test vehicle is being used for the development of the required technologies. The system is able to detect driving distance and velocity of the vehicle by using encoder sensors. Direction of the vehicle is detected by a fiber optic gyroscope. Using a laser transmitter/receiver and poles with laser reflectors, the system is able to correct accumulated positional errors. The system uses image processing and analysis techniques for obstacle detection and recognition (Sugiura 1993).

3.2. Base, Surface Material, and Curb Placement

These operations involve placement of coarse grained materials (gravel or crushed stones) on the graded soil as a base layer. The base layer is then screeded and compacted. either asphalt or concrete mix material is spread on the base layer as a surface layer. The surface layer is then screeded and graded, then curbs are placed. Here the current research and development are discussed.

- Currently, automatic non-contacting grade and screed control systems represent the state-of-the-art technology in paving control operations. These systems use ultrasonic sound wave and laser beam sensors to control grade and pavement thickness. Most of these systems have ultrasonic devices attached to each side of the screed and are controlled by a central control box at the rear of the screed. When a laser system is used, a rotating laser transmitter sitting away from the paver sends signals to a laser-sensitive receiver on the paver. These signals transmitted to a microprocessor which controls the blade elevation accordingly.

- A robotic asphalt paver has been developed by the Advanced Construction Technology Center and some of the major construction and engineering companies in Japan. The paver has an automated system for feeding asphalt mix, controlling pavement thickness, steering operation, controlling screed extension, and receiving the asphalt mix. The robotic paver utilizes ultrasonic sensors to control the asphalt mix feeding quantity and pavement thickness. For steering and screed extension control, the system uses laser and vision sensors, image processing techniques, and fuzzy control. The robotic asphalt paver has a total weight of 13,000 kg, and a paving width of 2.5 - 4.5 m (Umeda 1993).

- Other similar automated equipment in the area of paving control systems include Blaw-Kontrol II, which is developed by Blaw-Knox Corp., in the USA, for automatic screed control, Agtec's automatic ultrasonic and laser control system, by Agtec Co., Blade Pro Paver Control System by Spectra-Physics, Dayton, Ohio, Computerized Profiler Control (CPC) system by Caterpillar, and many others.

- Miller Formless System Co., in the USA, has developed automated slipform machines for curb and gutter construction. These machines (M1000, M7500, M8100, and M9000) are of different sizes and can perform various tasks, such as forming standard curbs and gutters, pouring barrier walls, bridge parapets and bifurcated walls, and paving different widths (up to 18 ft) in straddle position (Skibniewski 1990).

3.3. Road Maintenance and Other Supportive Activities

These work activities include defect detection and treatment, and other supportive activities such as lane marker installment, line painting, sign placement, snow removal, potential hazardous spill testing, bridge inspection, grass mowing, and litter bag collection. The following are examples of automated systems:

- A field prototype of a robotic pavement crack sealing system has been developed by Carnegie Mellon University and the University of Texas at Austin in the USA. This system combines vision and laser range sensors for crack detection and mapping. The crack treatment is performed by an X-Y table manipulator, similar to a large scale pen plotter, with three mounted tools. These tools include an infrared laser range sensor for depth information, a heated air torch for cleaning the cracks, and a sealing wand for filling the cracks with sealant material (Haas 1992).

- Another similar system (vehicle) for pavement crack sealing, called Robo-sealer, is being under development by the California Transportation Department (Caltrans) and the University of California at Davis in the USA. This system consists of two different crack sealers. One is mounted on the side of the vehicle platform for sealing longitudinal cracks found at the edge of the pavement. For general cracks, the other crack sealer is mounted on linear slides at the rear of the vehicle.

- An automated pothole repair system is under development at Northwestern University's Industrial Research Laboratory in the USA. A laser range and vision sensors are used to determine the outline and depth of the pothole. The pothole edges are then cut and routed by a vertical-mill cutter. A vacuum system is used to remove water and debris from the hole. The combined data from the laser and vision sensors are also used to map the pothole and generate a manipulator trajectory needed to spray the patch material.

- Another similar pothole patcher **(Puff)** has been developed by One Man Inc. in the USA. In addition to the automated pothole patching, The system provides different traffic control warnings and signals to ensure the safety of the operator and the public (Hsieh & Haas 1993).

- A robotic manipulator for underwater inspection of bridges has been developed by Sonsub Environmental Services of Houston in the USA. The system uses a 60 ft. (18m) computer controlled telescoping arm to move a sonar probe below the surface of the water to inspect the bridge pilings for scour holes.

- Research is currently being conducted by the University of California at Berkeley on a Remotely Operated Vehicle (**ROV**) to sample an unknown potentially hazardous substance and deliver the sample to a dispensing system on top of a Remotely Operated Laboratory (**RLAB**) (Demsetz 1993).

4. ECONOMICAL CONSIDERATIONS FOR AUTOMATED ROAD CONSTRUCTION AND MAINTENANCE

In addition to the technical considerations, robotic applications have to be economically justified and carefully evaluated in terms of their costs and benefits. In one study (Hsieh & Haas 1993), the costs of research and development for an automated pavement crack sealing system have been estimated to be from one to two million dollars. The economic analysis of the system shows a potential net annual savings of approximately three million dollars. The long term benefits to the public could be in the form of a higher standard of living (i.e., improved roadway system enhances the transportation and trade system in the country and leads to economic growth), and cleaner environment (i.e., better quality roads and quick maintenance actions lead to higher travel speed and less stop-and-go cycles, which result in less fuel consumption and less air pollution). But in some cases the research development, and marketing costs are incurred by the private sector. If that was the case, these costs could be included in the ultimate price of the equipment. The selling price of automated equipment depends on many factors (Skibniewski 1988), such as research and development costs, manufacturing costs, marketing and overhead costs, and market demand and supply of such equipment.

Because of the relatively high costs incurred by a construction firm for operating and investing in robotics, it is very critical for the construction firm to optimize the performance of its automated equipment whenever it is feasible and for as many as possible (Skibniewski 1991). A computerized system called Construction Robotic Equipment Management System (**CREMS**) (Russell 1990) has been developed in order to aid the construction management personnel in decision making regarding the implementation of automated equipment or any other scarce resources. The system also helps in optimizing the performance of the automated equipment by assigning it to the most appropriate construction project.

5. CONCLUSIONS

Recent advances in the development of automation technologies provides road construction and maintenance with opportunities to improve work productivity and quality, to reduce labor costs, to decrease worker exposure to road hazards, to minimize impeding traffic, and to comply with current environmental regulations. Current applications of automation in road construction and maintenance prove these facts, and shows that costs of automation can be justified by optimizing the performance of the automated equipment.

6. REFERENCES

1. Demsetz, L. A., et al. (1993). "RLAB: A Remotely Operated Laboratory for Improved Management of Hazardous Spills" Proc., 10th ISARC, Houston, USA, 447-454
2. Haas, C., et al. (1992). "A Field Prototype of a Robotic Pavement Crack System" Proc., 9th ISARC, Tokyo, Japan, 313-322
3. Huang, X. D., and Bernold, L. E. (1993). "Robotic Rock Handling During Backhoe Excavation" Proc., 10th ISARC, Houston, USA, 355-362
4. Homma, K., et al. (1993). "Research on Components of Underground Excavation Robot" Proc., 10th ISARC, Houston, USA, 245-252
5. Hsieh, T., and Haas, C. (1993). "Costs and Benefits of Automated Road Maintenance" TRB Annual Conference, Washington, D.C., USA
6. Kanzaki, T., et al. (1993). "Survey Robot Using Satellite GPS" Proc., 10th ISARC, Houston, USA, 479-486
7. Okano, M., et al. (1993). "Development of Earthwork Progress Measurement System Using GPS" Proc., 10th ISARC, Houston, USA, 471-478
8. Russell, J. S., et al. (1990). "Framework for Construction Robot Fleet Management System" J. Const. Engrg. Mgmt., ASCE, 116(3), 448-462
9. Derek, S. (1992). "LUCIE the Autonomous Robot Excavator", Mgz. Industrial Robot, UK
10. Sidney, A., et al. (1993). "Automating Inspection of Highway Pavement Surfaces" J. Transport. Engrg., ASCE, 119(1), 1-12
11. Skibniewski, M. J. (1988). "Robotics in Civil Engineering" Van Nostrand Publishing Co., New York, USA
12. Skibniewski, M. J., and Hendrickson, C. (1990). " Automation and Robotics for Road Construction and Maintenance" J. Transport. Engrg., ASCE, 116(3), 261-271
13. Skibniewski, M. J., and Russell, J. S. (1991). "Construction Robot Fleet Management System Prototype" J. Comput. in Cvl. Engrg., ASCE, 5(4), 444-463
14. Sugiura, S. Y., et al. (1993). "Autonomous Dump Trucks System for Transporting and Positioning Heavy-duty Materials in Heavy Construction Sites" Proc., 10th ISARC, Houston, USA, 253-260
15. Umeda, R., et al. (1993). "Development of A Robot Asphalt Paver" Proc., 10th ISARC, Houston, USA, 261-268