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Automation in Transportation System Construction and Maintenance

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AUTOMATION IN TRANSPORTATION SYSTEM CONSTRUCTION AND MAINTENANCE

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Foreword

Carl T. Haas, Chairman

Automation in transportation system construction and maintenance operations has been advancing at an accelerated pace in the past two decades. Examples include automated asphalt paving and man-machine balanced road compacting being developed in Japan and Europe; automated earth moving and off-road haul systems being developed by major U.S. equipment manufacturers; and more experimental prototypes being developed in U.S. university laboratories. Skilled labor shortages, increased safety issues, reduced road user costs, technological competitiveness, and technological advances are all motivating these developments.

Automated construction equipment is beginning to enjoy commercial success. Controls for the equipment are becoming similar to video games with ergonomic joysticks, graphical interfaces, and sensory alarms. Furthermore, the GPS, the Internet, and wireless technology enhance the situational awareness of the operator while controlling the remote equipment within various features and obstacles of the worksite.

The main objective of this Circular is to provide a summary of emerging technologies for automated transportation system construction and maintenance. It is directed toward people in this field in order for them to keep up with new technologies. The Circular first gives a description of the state-of-the-art enabling technologies for automation in this area. It then introduces several classes of automated systems in applications such as earth moving, compaction, and road construction and maintenance.

This circular has been reviewed by TRB staff representatives and the Committee on Applications of Emerging Technology.

Keywords*: Automation, Construction, Maintenance, Transportation, Technology, Laser Positioning, Graphical Control, Teleoperation, Machine Vision, Human-Machine Interface*

Automation in Transportation System Construction and Maintenance

1 INTRODUCTION

Transportation system construction and maintenance has experienced significant recent advances in automation. Such advances will likely accelerate in the future. They are founded on enabling technologies such as computing, positioning systems, advanced control methods, and graphical interfaces. This Circular begins by describing the relevance of these enabling technologies to automation in transportation system construction and maintenance. It then focuses on classes of applications, including earth moving, compaction, road construction and maintenance, and intelligent transportation systems.

2 KEY ENABLING TECHNOLOGIES

2.1 Computer Technology

Computing is a key enabling technology for field automation. Computer hardware alone has been increasing in capability at a rate of 30 percent per year [Hendrickson, 1995]. The use of computer technology allows a major reduction in operator stress and fatigue associated with routine decision making, while providing alarms and other tools for heightened awareness when conditions warrant immediate operator attention. Computer technology also provides opportunities for data integration across construction sites and over time. Software also can be used to provide resolved motion capability where needed.

It is difficult and fatiguing for an operator to work with a machine that has a natural set of degrees of freedom, or directions of operation, to work on a project that has a set of natural movements that are misaligned with the operator's machine. Such work requires a continuous adjustment of several controls at the same time and is both tiring and confusing. Examples include large manipulators, excavators, and man-lifts. Computer software provides superior control, together with ease of use, by using inverse kinematics and advanced control schemes to achieve resolved motion control. For example, an excavator can now be commanded to dig at a near perfect level.

2.2 GPS and Laser Positioning Technology

In recent years, the use of Global Positioning Systems (GPS) and laser positioning sensors in the construction industry has become very common. GPS and laser positioning technology can be used to achieve many advantages such as automated control of equipment. For example, installing positioning sensors on construction manipulators and excavators would eventually lower labor costs, and improve machine performance and work quality, thus increasing job efficiency in construction sites.

Two types of real-time positioning instruments are used widely in the construction industry. These are: (1) GPS including Differential GPS (DGPS) and On-The-Fly DGPS (O-T-F DGPS), and (2) laser-based 3-D Real-Time Positioning Systems (3D-RtPM™).

GPS is a satellite-based positioning system, and it is mainly used for surveying large areas and monitoring construction equipment or transportation vehicles. DGPS and O-T-F DGPS are used in applications where better accuracy is required. Figure 1 illustrates a Computer Integrated Construction (CIC) system as a typical application of GPS positioning technologies [Peyret, 1999a]. The CIC system is composed of three main subsystems. First, a ground sub-system provides equipment with geometric data about the worksite as well as guidelines for operation. Second, a positioning subsystem provides the system with the necessary position data. Third, an onboard subsystem controls all the functions supposed to be realized by the system on the machine itself.

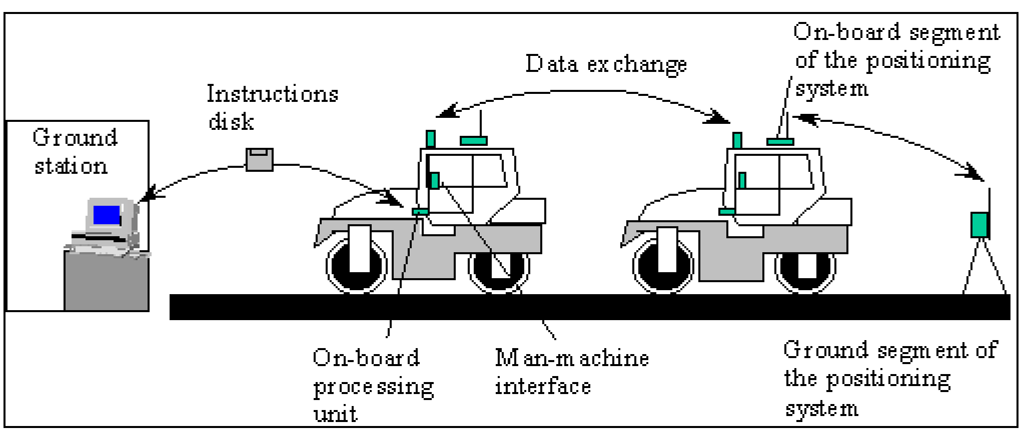
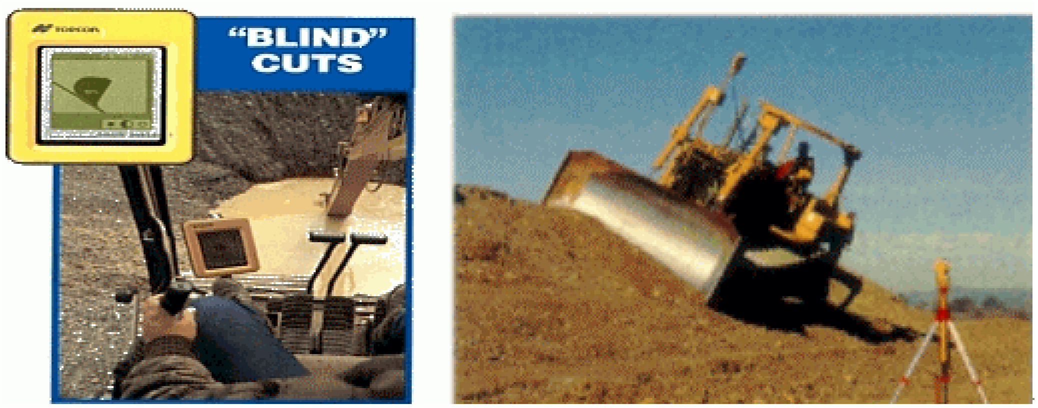


Figure 1 The basic architecture of a Computer Integrated Construction (CIC) system.

Laser positioning systems such as 3D-RtPM can be used for site surveying, layout, as-built modeling, inspection, and equipment control [SPSi, 1996]. They offer accurate, real-time, three-dimensional position information of points or objects. After the setup of transmitters, any position information can be obtained easily by positioning the receiver to the points for measurement (Figure 2). Laser positioning systems may also provide a field link to the engineering office to allow craftspeople, foremen, surveyors, and other on-site personnel to transfer field information to CAD design data and relate the design data to the construction environment [Chun et al., 1997].



(a) Excavator Touch Series 5 (b) LS-B2 Machine Control Laser Receiver

Figure 2 Construction Machines Equipped with Positioning Sensors.
(Photo courtesy of Topcon Laser Systems, Inc., 1998.)

2.3 Teleoperated Control

Teleoperation or remote control capability for construction equipment is a natural stepping stone towards full autonomy. Teleoperation is defined as controlling equipment from a distance. Typically, teleoperated equipment allows one operator to do the work that previously required several workers exposed to hazardous or unpleasant working conditions. To control the teleoperated equipment, the following components are required: remote control of the device, visual feedback of the tool and workspace, and usually some forms of computer assistance. Figure 3 shows a typical teleoperation architecture. Examples of its application include large scale manipulators and shadow vehicles for road maintenance crews.

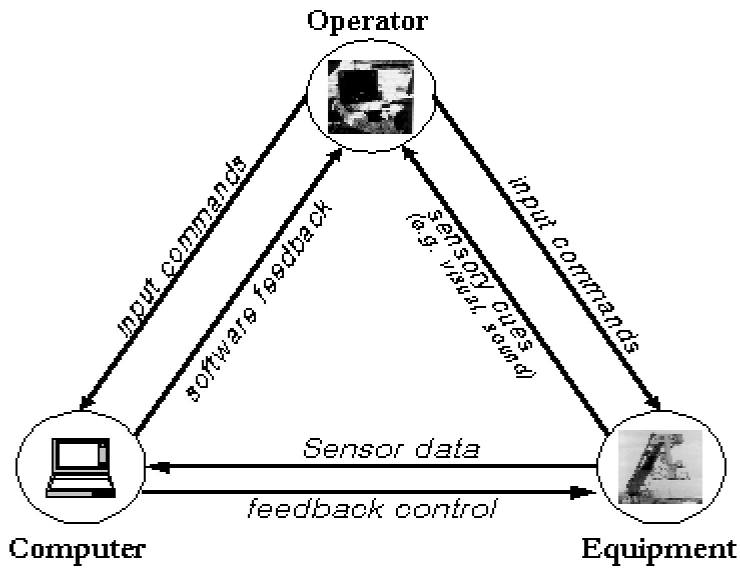


Figure 3 Typical Teleoperation System Architecture.

2.4 Graphical Control

Graphical control involves the use of a computer-generated model of the equipment in its operating environment as feedback to the operator. Accurate and up-to-date workspace models are required. Although these are not feasible in many situations, if the work environment is fairly static, then a good model can be generated (Figure 4). With this model, real-time updates of the equipment moving through its environment can be shown on the computer screen. With virtually unlimited view changing and zooming capabilities, the operator can actually have a better idea of the position and orientation of the device than with standard vision systems. Another benefit of graphical control is the ability to simulate the movement of the equipment through a difficult environment. This allows the operator to make mistakes without damaging the equipment and to preprogram the movements of the equipment, but it is of limited use if an accurate workspace model is unattainable. Graphical control merges information from several sensors or even several fundamentally different technologies to improve accuracy in decision making while the operator works from a secure, environmentally-controlled workstation. Examples of graphical control application include automated earth moving and compaction.

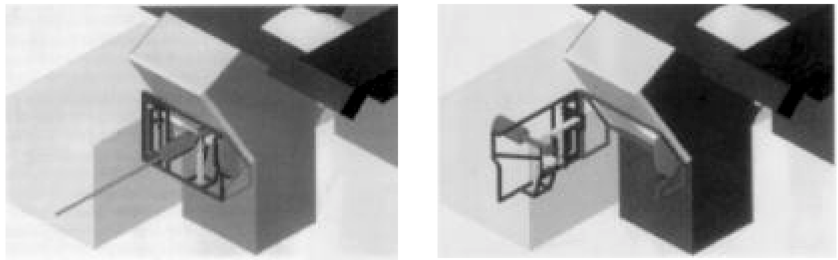


Figure 4 3-D Graphical Interface for Automated Clinker Clearing Machine Control. (Photo courtesy of Field Systems and Construction Automation Laboratory at the University of Texas at Austin.)

2.5 Machine Vision

The use of remote video cameras is a common method for providing visual feedback to the operator. These can be arranged in such a manner as to provide several different views of the equipment in its workspace. This artificial operating environment provides the user with the necessary visual feedback to control the device. Once a remote video signal is obtained from a piece of equipment, machine vision algorithms can be employed to enhance the control of the device. Machine vision uses different schemes to search an image for specific items. For example, machine vision algorithms could be used to look for obstacles that need to be avoided or for cracks in buildings (Figure 5). The operator can reduce the search area, and also the processing time, by selecting the regions of the image that contain the desired items. The vision algorithms are then used to tune the operator's inputs. Two cameras can be used to produce a 3-D image which can provide an added depth dimension to the scene. These machine vision processes can greatly reduce the amount of human interaction necessary to properly operate a piece of equipment, and the overall cycle time by automatically performing some, if not all, task generation.

Figure 5 Crack Detection and Representation Using a Machine Vision Algorithm.

2.6 Actuator Feedback Control and Sensory Cues

The actuators of an automated machine can be controlled by several different methods. The most basic is for the operator to use ON/OFF mechanical links to control each actuator. A slightly modified form of those are proportional controllers which allow for the speed of actuation to be increased as each controller is moved further away from its neutral position. Both of these rely on the operator's senses for feedback control. However, more advanced and capable forms of actuator control involve the use of a computer. These control systems vary from simple control loops, which vary output signals to the actuators based on each one's distance from some desired parameter such as position or velocity, to very complex systems that allow for contoured, or resolved, motion. Resolved motion is attained by a computer controlling all of the actuators together in order to have the tool of the equipment follow a prescribed path. This could be just a straight line along a surface or a complex curve in three dimensions. There are existing teleoperated devices which employ each of these types of computer and human feedback control.

Sensory cues include sound alerts such as proximity sensors that warn the operator when the equipment moves dangerously close to an obstacle. Also, the vision of the user can be used as feedback control of the position and velocity of the equipment. A third form of sensory feedback is the tactile feedback in a force-reflective controller which can alert the operator when an item has been grasped or an obstacle has been encountered. These and other sensory cues allow the judgment of the operator to be a major factor in the control of automated systems.

2.7 Human-Machine Interface

The degree of difficulty faced by a user when interacting with a machine depends greatly on the sophistication of the actuator control scheme. The human-machine interface for a piece of construction equipment or a robot can be as little as the operator viewing the machine in its environment, possibly using remote video capabilities, and controlling each of the actuators through the use of joysticks or control levers to move the equipment to its desired configuration. This type of interface can be very difficult if no resolved motion control algorithms are used, and it relies heavily on the experience and visualization skills of the operator. A more exotic human-machine interface is the spatially correspondent, or telechiric, controller. This is a force-reflective controller that is kinematically equivalent to the slave manipulator. The position and velocity of the controller are representative of the manipulator, and any forces acting on the manipulator are felt by the controller. This is a very intuitive interface, which requires many sensors, precision tooling and a complicated computer control scheme in order for it to be implemented.

The human-machine interface could also be through the use of a touch-sensitive screen, mouse, or other pointing devices (Figure 6). These all would use the coordinates of the cursor on the screen to determine the required action of the equipment. The desired path for the tool could be drawn on the screen and then the computer could generate the proper commands for the desired motion. The drawback to this form of human-machine interface is that it is usually limited to just two dimensions. All of the different interfaces require varying degrees of computer complexity and operator skill. Selecting the proper interface for a piece of equipment is an important and non-trivial task.

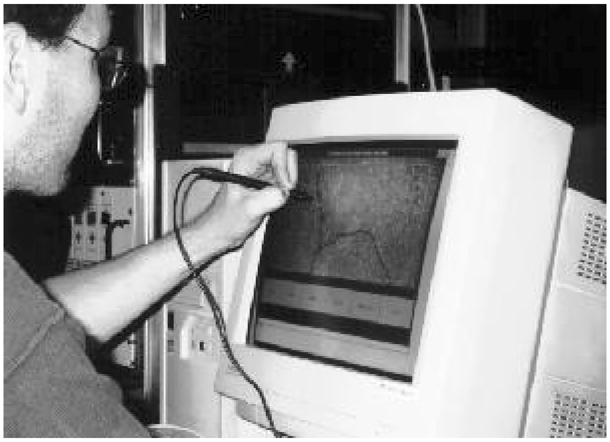


Figure 6 An Example of Human and Machine Interface Using a Touch-Sensitive Screen.

2.8 Image Modeling Technique Using Forms

Condition data acquisition and representation is a key element in automated infrastructure maintenance and rehabilitation. Various models have been proposed and implemented for this purpose. Since such a model is concerned primarily with geometric aspects of infrastructure, a primary representation using strong, weak, and nonparametric forms is appropriate [Haas, 1997]. Forms represent infrastructure design and condition elements and can be used for analysis, visualization, and work planning for automated maintenance (Figure 7). They can be associated with non-geometric data such as dates and specifications using databases linked to CAD packages. Graphs and hierarchical structures also can be used to organize the forms.

Strong forms include parametric prisms, cylinders, blocks, etc., that represent, for example, pipes, beams, columns, and floors. Weak forms have been defined by Hirschberg [Hirschberg, 1996] as parametric objects with "rubberbanding" capabilities. An example is a rectangle which may become an irregular four-sided polygon to fit a distorted door frame. A cylinder may grow a joint to represent a bent pipe. Splines may also be considered weak forms. Nonparametric forms include wire nets that may represent contour data, polylines that may represent cracks, and occupancy arrays or octrees that may represent amorphous volumes or grossly deformed objects. In fact, nonparametric forms may be simplified, fit to, or idealized as weak forms, and weak forms as strong forms. From raw data to strong forms, this becomes a stochastic matching and fitting process. Fusion of 3-D range data clouds is an example. Choice of forms for representation is driven by the maintenance application.

As a similar modeling technique, an innovative image capturing system using laser scanners and photos has been developed by As-Built Data Inc. The system can accurately create 3-D CAD models from 2-D photos using a laser-powered image scanning system, allowing the designers and contractors to keep good records of the facility which is being built or maintained [ENR, 1998a].

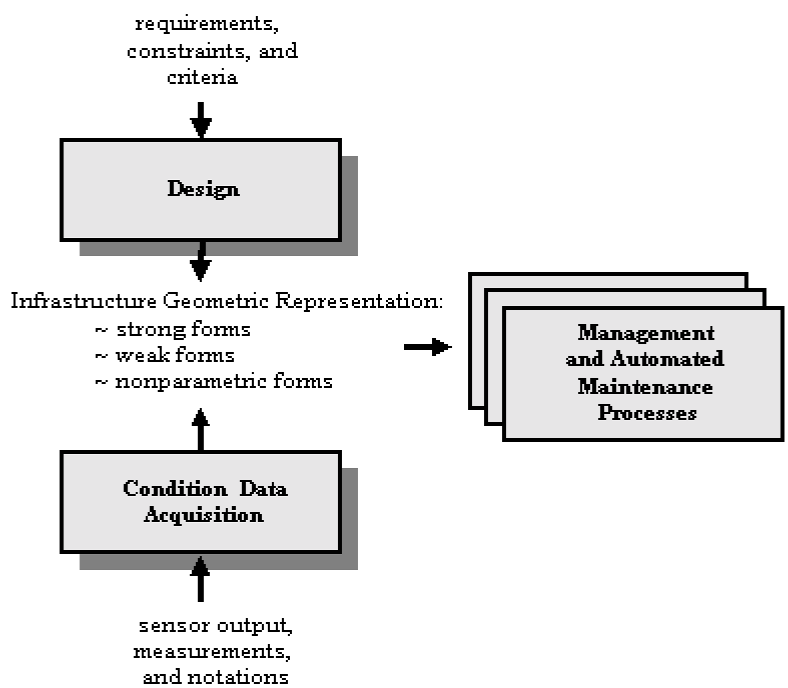


Figure 7 A Model Structure for Automated Infrastructure Maintenance Using Representational Forms.

3 APPLICATIONS IN AUTOMATED TRANSPORTATION SYSTEM CONSTRUCTION AND MAINTENANCE

Numerous research and implementation efforts are currently underway to automate conventional infrastructure construction, condition assessment, and maintenance activities. As examples, several systems in the following areas will be highlighted and briefly described in this section.

- Earth Moving
- Compaction
- Road Construction and Maintenance

3.1 Earth Moving

Excavation of soil and rock or trenches is a high-volume, dangerous, and repetitive construction operation. Skilled operators with many years of experience are required to efficiently maneuver excavators such as backhoes, front-end loaders, dozers, and scrapers, and graders. They also must avoid damage to unexpected underground utilities, and avoid accidents (i.e., rapid collapse of trench-wall) during excavation. Rework due to errors or incidents related to conventional earthwork is very expensive, time-consuming, and unproductive. In recent years, a number of studies and development efforts to automate conventional excavating, trenching, pipe-laying, and grading operations have been undertaken by several research institutes and major equipment manufacturers. As an example, one automated earth-moving system uses real-time 3-D locating to work directly from CAD models, eliminating wasteful excavation and earth-moving and repeated placement of grade stakes. Such robotic excavation and earth moving systems are presented in the following sections.

Robotic Excavation and Pipe Laying

A real-time graphical programming model was developed for a manipulator used for excavation and pipe laying. It used a long-range, 3-D positioning system to give the operator of the equipment its exact position in a real-time CAD simulation. The laser-based positioning sensors were on the cabin of the excavator and the position of the end-effector was obtained from encoders on the joints. Thus, one can change to any viewing angle and any amount of zooming within the simulation to precisely see the progress of the excavation. A metal detector for sensing buried utility lines was installed and provided the user with a warning signal when lines were detected. The user interface with the excavator can be accomplished with remote joysticks, which allow the operator to be at a safe distance from a hazardous environment [Bernold, 1996]. This system is in a field prototype system (Figure 8).

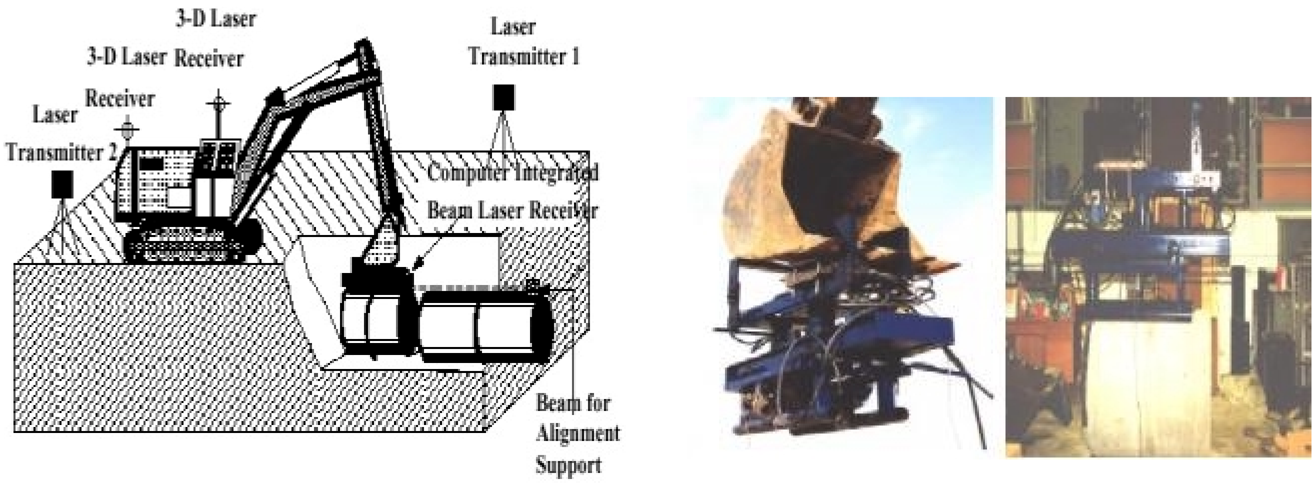


Figure 8 Robotic Excavator and Pipe Laying Machine. (Photo courtesy of Construction Automation and Robotics Laboratory (CARL) at North Carolina State University.)

Haz-Trak

Haz-Trak is a remotely controlled excavator developed by Kraft TeleRobotics. It was designed to be fitted with a bulldozer blade for grading, backfilling, and leveling operations [Jaselskis and Anderson, 1994]. For ease of control, its manipulator (a robotic arm) uses a combination of force-feedback and master-slave control so that the robotic arm instantly mimics the movement of the control handle. For excavation, the system operator moves the handle in a scooping motion. The force feedback system responds through the control handle so that the operator can actually feel when the digging gets tougher. Other features include “task recall” which enables the operator to program a series of routines for later repetition. In this way, the operator could preview a critical procedure before actually performing the task. The operator can also set limits on the motions of the manipulator to prevent contacting obstacles. Such control is for specialized and remote operations. It is expensive but effective.

Teleoperated and Automated Maintenance Equipment Robotics System

A radio-controlled front-end loader has been developed in an effort to remove the operator from potentially dangerous environments such as clearing highways after an avalanche, clearing landslides, and cleaning up hazardous materials. This backpack-mounted and joystick-controlled device (Figure 9) allows the operator to be several hundred meters from the site. The remote control package for this system is composed of a micro controller-based operator control unit, a full duplex spread spectrum RF modem, and an onboard computer-based control unit. However, the only feedback for this control device is the vision of the operator at the remote site [West, 1995].

Figure 9 Teleoperated and Automated Maintenance Equipment Robotics (TAMER) System during Operation. (Hendrickson, 1995. Automation and Robotics in Highway Design, Construction, and Maintenance, *TR NEWS*, No. 176: 2-23.)

Automated Earth Moving System

In the Pentagon's Technology Reinvestment Project's first round of awards, a team including Magnavox Electronic Systems Co., Spectra-Physics Laserplane Inc., and the Army Corps of Engineers was awarded U.S. $17,700,000 to develop (GPS) and laser technology to control earth-moving equipment blades. The team promised earth moving "to accuracy of a centimeter" without site and topographic surveys [ENR, 1993]. A graphical interface is used in the control scheme that has been developed.

Caterpillar Computer Aided Earthmoving Systems (CAES)

In a similar advance, a Computer Aided Earthmoving System (CAES) has been developed by Caterpillar. The CAES is equipped with high-accuracy GPS receivers, data radios, and displays to provide the system operator and the site manager with a variety of real-time information regarding the execution of earth-moving tasks. The computer system gives the operator a graphical interface with this information. The GPS receiver obtains real time information on the location of soil such as latitude, longitude, and elevation. Using such information, the system operator can easily determine the exact amount of excavation, backfill, or grade, minimizing wasteful earth-moving and repeated placement of grade stakes. At the same time, the project manager, engineers, and the superintendent share this information at their respective locations. All necessary devices can be mounted on conventional earth-moving equipment such as bulldozers and motor graders [Caterpillar, 1997].

3.2 Compaction

Compaction is an important task for improving construction material stability during site work. The field compaction operation consists of compacting the soil using various compacting equipment. Subsequent in situ soil testing (surface moisture and density tests) is done until desired compaction is achieved. In the conventional compaction process, the equipment operator will not have prior knowledge of the number of passes that is required to achieve compaction as per the specification and hence may over or under compact the soil. In the case of over compaction, unnecessary manpower and equipment operating costs are expended, and under compaction results in rework which requires additional time and costs by failing the required moisture and density tests. Further, field compacting is a trial-and-error process and prone to human errors and judgement because of varying soil conditions and rough terrain.

Computer Integrated Road Compactor (CIRCOM)

The CIRCOM project is supported by the European Commission, under the Industrial & Materials Technologies Program Brite-EuRam III. The CIRCOM prototype has been developed and experimental trials have been done successfully in Villedieu-Les-Poeles (Normandy, France) at the beginning of September 1998 (Figure 10). The CIRCOM is based on the system architecture comprised of three subsystems. The role of the ground subsystem is to provide the compactor with geometric data about the worksite, coming from CAD data, as well as guidelines for operation, and to compute compacting results and some statistics about the work achieved. The role of the positioning subsystem is to locate precisely and in real-time the compactor by using GPS, in real-time kinematic (RTK) mode as well as dead reckoning sensors (Doppler radar, encoder and fiber-optical gyrometer). The role of the onboard subsystem embedded on the compactor is to memorize and complete instruction data, position data, work done, and to manage a man-machine interface (MMI) which assists the driver in compacting (Figure 11). The experimental trials showed that the main functions required were fulfilled, in particular the performance of the positioning system, even inside GPS shadow zones, thanks to its innovative fusion between GPS and other sensors' measurements. Other multi-compactors' functionalities are currently under development (Figure 12) [Peyret 1999b].

Figure 10 The compactor used for the full-scale trials.

Figure 11 The onboard MMI of CIRCOM prototype during compaction.

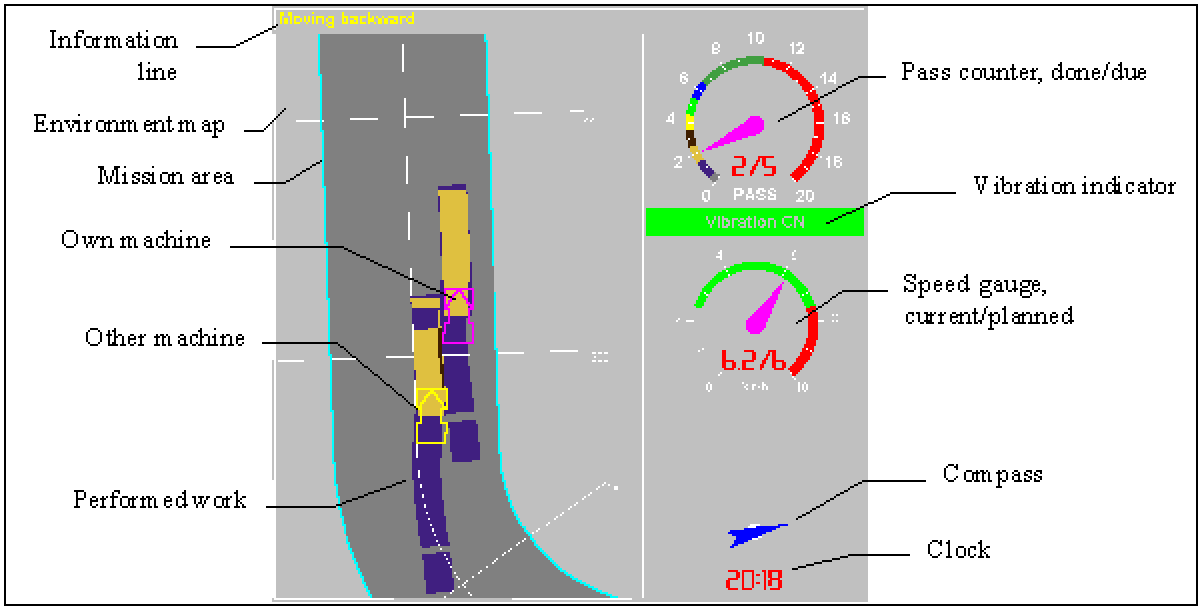


Figure 12 CIRCOM onboard subsystem main MMI for multi-compactors.

Automated Vibratory Compaction Using Onboard Compaction Meter

With an onboard compaction meter, the system operator can monitor the density of the soil on a continuous basis. The density of the surface base material is based on a correlation between the reaction forces of the surface. To measure the reaction forces between the surface and the drum, a sensor is mounted on the vibrating drum. When the reaction forces increase, the density of the surface base material increases. An onboard computer then converts the reaction forces into a relative value, and displays this value on the console so that the system operator can easily monitor the density of the base material being compacted, and stop the compacting operation when a desired density level is achieved. As an upgraded version of this, Hamm Compactors Inc., provides a more expensive and sophisticated onboard compaction meter that allows the system operator to document compaction results for all passes being compacted, including more display information in the cab of the equipment (Figure 13).

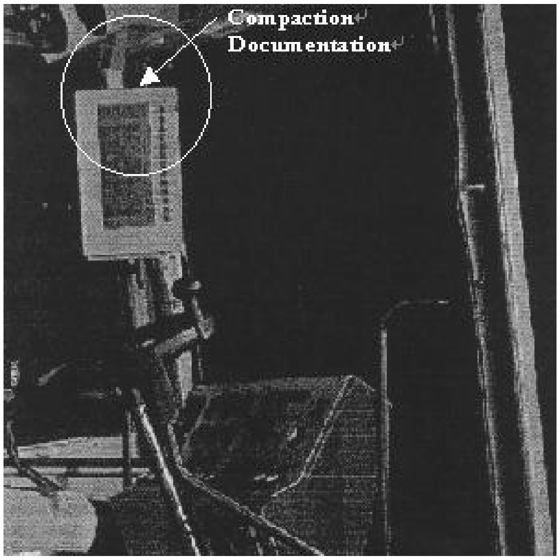


Figure 13 HAMM Compaction Documentation System (CDS) Onboard Compaction Meter System. (Photo courtesy of Hamm Compactors Inc.)

Automated Compaction Using GPS

An automated compaction monitoring system using differential GPS technology is being developed by Pennsylvania State University. The system allows operators to monitor the actual number of passes done by the compactor. In order to get real-time positioning information, two GPS receivers are utilized, one as a static base station and the other is placed on the compactor. Once the device records positioning information of the compactor, the real-time positioning information is then transmitted to a remote computer, through an appropriate wireless technology. Using the geometry of the compactor and the location of the positioning device, the software displays the areas covered by the compactor during operation. The covered areas are coded by colors, based on the calculation of the direction of motion and the number of drums. From this, the operator can proceed to compact until all surface locations reach a specific color on the screen [Oloufa, 1997].

Compaction Using Automatic Vibration Control System

A compactor with automatic vibration control system has been developed by Compaction America Inc. The system automatically selects the correct amount of vertical vibration needed to concentrate compaction on multiple passes of a newly laid pavement. On the initial pass, the system automatically sets vertical vibrations for deep and fast compaction. Then it adjusts the horizontal-to-vertical movement ratio when the operator reverses the roller's direction. With this automatic fine-tuning feature, the roller's impact could be adjusted so that the machine's performance can be matched to constantly changing conditions of the increasingly compacted surface, thus improving work efficiency and quality [ENR, 1998b].

3.3 Road Construction and Maintenance

Highway networks in developed nations are aging, while the volume of traffic they support is increasing. At the same time, costs for road construction and maintenance are rising, and environmental regulations are becoming stricter regarding safety and minimum environmental impact [Haas, 1997]. Automated road construction and maintenance has high potential to improve worker safety, productivity, and job quality. For automated road maintenance, user fuel consumption and delays also could be reduced by minimizing interference between traffic and maintenance crews. Reductions in labor costs are potentially high as well.

In recent years, a number of automated systems have been developed and are commercially available in the highway construction and maintenance area. For example, at the University of Texas at Austin, an Automated Road Maintenance Machine (ARMM) is being developed to automate the process of sealing pavement cracks and joints. Automated pavement crack and joint sealing will improve safety by removing laborers from dangerous work zones, it will reduce direct costs, and it will allow work at night to reduce road user delays. In this section, several automated road construction and maintenance systems are highlighted as examples.

3.3.1. Paving

Robotic Paving Machine

This machine uses machine-vision image processing routines to follow the curb or a chalk line to control its screed and steering [Hagiwara, et al., 1995]. The vision sensor detects the edge of the curb by using a laser beam that hits the curb at an angle. It can follow a chalk line by detecting the difference between bright and dark values in the image. There is an audible alarm that rings if a person is between the paver and the dump truck during its material feeding mode. The screed position and paving thickness are controlled by a computer system which uses feedback from the solenoids and other sensors to maintain a uniform finish.

Pavers with Non-Contacting Sensors

Automatic paving systems using non-contacting sensors are being currently used in the paving industry. As one of commercial products, for example, PAVER SYSTEM FOUR can be mounted and installed in any existing paver (Figure 14). PAVER SYSTEM FOUR is composed of two control boxes, two Sonic Trackers™, and a slope sensor. The Sonic Trackers™ are used to control elevation by measuring the distance to a physical reference using sound pulses, as in sonar sensors. The slope sensor includes a precision electronic device. Once the slope sensor is tilted, an electronic signal is generated. By measuring this electronic signal, the slope sensor can precisely calculate the slope of the screed. During paving operation, the components work together to determine the screed's position relative to desired grade and generate correction signals to keep the screed on grade [TOPCON Laser Systems Inc., 1998].

Figure 14 PAVER SYSTEM FOUR. (*Source:* PAVER SYSTEM FOUR; Product Brochure of TOPCON Laser Systems Inc. 1998.)

Automated Reflective Pavement Marker Placing

The precise placement of pavement markers was determined to be too difficult to completely automate. So, the operator was taken from outside in dangerous environment and placed inside the truck cabin. Here, the user of the equipment uses a remote video system to view the road surface and selects the position for marker placement by moving the cursor to the desired location. A coordinate transformation converts the cursor position into the workspace position and the marker is installed [Bernold, 1995]. This machine is at the prototype stage

(Figure 15).

Figure 15 Telerobotic Raised Pavement Marker Applicator. (Photo courtesy of Construction Automation and Robotics Laboratory (CARL) at North Carolina State University.)

3.3.2 Roadway Maintenance

Automated Road Maintenance Machine (ARMM)

Through trial and error, over approximately 9 years, the Automated Crack Sealer has achieved a good balance between human and machine functions for automated pavement crack and joint sealing. The crack sealer uses an XY-manipulator with a rotating turret to blow, seal, and squeegee cracks and joints in one pass, thus greatly improving system productivity. While the manipulator is moving within its work area, its frame is stationary. Sealing cracks in one work area and then moving to the next work area is considered one work cycle. To control the crack sealer through a work cycle, five steps are required. These include: (1) image acquisition; (2) crack mapping and representation; (3) line snapping and editing; (4) path planning; and (5) manipulator and end effector control. It is also anticipated that the teleoperated crack and joint sealing technologies should be applicable to a wide variety of infrastructure crack and joint sealing applications. Partial modifications of the algorithms and tools used in the ARMM would eventually have broader applications in automation of infrastructure inventory geometric data acquisition and use or maintenance or inspection of civil works (pothole filling, automated routing, message painting, and marker placement) [Kim, 1997]. The ARMM is at the commercial prototype stage (Figure 16).

Figure 16 UT Automated Road Maintenance Machine in the Field. (Photo courtesy of Field Systems and Construction Automation Laboratory at the University of Texas at Austin.)

Robotic Bridge Paint Removal

This prototype robot uses a video camera and ultrasonic sensors as feedback to the operator who uses joysticks to position the end-effector of the peeper crane near a bridge beam (Figure 17). At this point, the video camera continues to be used as the operator moves along the beam to find a corroded section. Then, a machine vision algorithm determines the position of the beam that is to be blasted. Visual feedback is provided again by the remote video system for verification that the bridge beam was cleaned [Bernold, 1995].

Figure 17 Teleoperated Bridge Paint Removal Machine. (Photo courtesy of Construction Automation and Robotics Laboratory (CARL) at North Carolina State University.)

Automated Snowplow Machine

The human-machine interface for this device employs a joystick or a touch sensitive board to select the point where the plow will cast the snow [Fukuda, 1993]. The joystick is moved in the XY plane and the touch panel is a 20m by 20m grid with 1m increments. The computer controls the direction and speed of the cast snow using feedback from the casting actuators in order to achieve the desired cast point. Verification can be achieved by using the operator’s vision of the snow being cast as well as a panel of LED’s under the touch panel.

A more advanced snowplow machine using state-of-the-art technology is currently being developed by a consortium, including the transportation departments of Iowa, Michigan, and Minnesota; the Center for Transportation Research and Education (CTRE) at Iowa State University; and several private vendors. The prototype snowplow is equipped with GPS, LCD display data recording system inside the cab, infrared air/pavement temperature sensor system, power booster, anti-icing and prewetting equipment, high-intensity lights, friction meter, and reverse obstacle sensors (Figure 18). The system records all data from sensors and they are directly used to operate the prototype snowplow machine. With the multi-sensors, the snow throwing operation could be performed in more efficient manner. Fatal incidents related to the snow throwing operation could also be prevented by using the high-intensity lights and reverse obstacle sensor. System performance evaluation and feasibility analysis for its commercial use are currently being undertaken [Wallace, 1998].

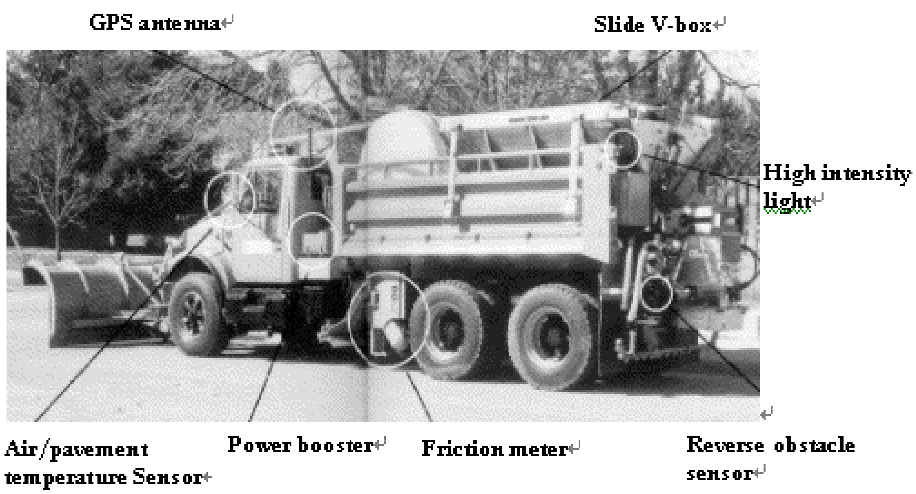


Figure 18 Automated Snowplow Machines. (*Source*: Wallace. 1998. Dream Snowplow Takes Shape, *TR NEWS*, No.19710-14.)

Remotely Driven Shadow Vehicle

The Minnesota Department of Transportation is developing a remotely driven shadow vehicle (RDV). Typically, the shadow vehicles are used to decrease the risk for highway workers, but still put the driver of the vehicle in a dangerous work environment. The RDV can eliminate this danger by allowing the driver to operate the vehicle using a remote control unit from a comparatively safe roadside (i.e., shoulder). With the remote control unit, the operator automatically controls the vehicle's steering, accelerator, and brakes as well as the lights, turn signals, and horn. Since the RDV is almost fully electronic and modular, any problems during operation can be easily diagnosed using a portable computer, and fixed relatively quickly. For commercial use, the RDV is now being thoroughly evaluated by the Minnesota DOT. The vehicle can be used as a conventional dump truck, if not in use as a RDV. The RDV also could be modified to automatically follow stripe-painting vehicles without requiring an operator to control the truck from the shoulder or the cab [FOCUS, 1998].

4 SUMMARY

Numerous efforts are currently underway to automate transportation system construction and maintenance activities. Productivity improvement, improved safety, improved quality, and reduced road user costs motivate these developments. This Circular first described key enabling technologies for automation of transportation system construction and maintenance. Then, it identified several examples of automated systems in the transportation system construction and maintenance area such as earth-moving, compaction, and road construction and maintenance.

In summary, automation is now entering the commercial phase. For example, equipment controls resemble video games with ergonomic joysticks, graphical interfaces, and sensory alarms. Robotic machines in the guise of traditional construction equipment are achieving commercial success. Although there is a lack of objective evaluations of performance, these advances will accelerate in the future. Development and implementation efforts for automation of transportation system construction and maintenance will also be expedited by supporting evaluation studies such as those done by Civil Engineering Research Foundation (CERF) and Highway Innovative Technology Evaluation Center (HITEC), and improved research funding. Through more publications, meeting, and workshops, knowledge of these advances will be improved as well.

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