Advanced Highway Maintenance and Construction Technology Applications

The Future Generation of Highway Machinery

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The Advanced Highway Maintenance and Construction Technology (AHMCT) Center was established in 1989 to investigate the application of advanced automation and robotics to highway maintenance and construction. The center is jointly managed by the California Department of Transportation (Caltrans) and the University of California, Davis (UCD). Base funding is provided by Caltrans, the Federal Highway Administration, UCD, and other public and private sources.

Highway maintenance and construction methods have improved considerably during the past several decades, but they continue to be labor intensive, hazardous, and inefficient. The application of technological innovation and systems improvement can speed construction and maintenance task completion, reduce associated costs, and make highways safer for their stewards and for travelers. Accordingly AHMCT Center objectives include

- Enhancing the safety of highway workers and the traveling public,
- Improving the efficiency of highway maintenance and construction activities,
- Improving the reliability of highway infrastructure,
- Minimizing congestion delays caused by highway maintenance and construction activities, and
- Reducing the environmental impacts of highway maintenance and construction activities.

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Research and development projects undertaken at the AHMCT Center are selected for their potential to meet significant challenges affecting safety, efficiency, and cost savings. The project life cycle begins with user surveys of perceived need and recommendation for service, process, method or equipment improvement, and innovation. Selected projects must meet the test of broad application and demonstrate strong potential for commercialization. Some projects may be pursued on their individual merit, provided the development is critically needed and independent and private research cannot be expected to bring the concept to commercial markets.

The preprototype research phase involves feasibility studies, cost-benefit analyses, and literature searches. Prototype development includes periodic design reviews and intensive evaluation by transportation maintenance and construction personnel.

End-user observations are incorporated into prototype improvements until a field-operational engineering prototype is developed that has been tested extensively in all environments by transportation workers. User comments and recommendations contribute to continued improvements until a reliable prototype is developed. Product manufacturers and marketing firms advance the product from its prototype stage to commercial marketability so that it can become a useful and cost-effective innovation of benefit to all public and private transportation organizations.

The center's research programs use emerging technology, including automation and robotics, to convert many labor-intensive, time-consuming, and tedious operations to safer, faster, and more efficient automated processes (*1*). Automation and standardization made possible through technological innovation improve productivity and reliability and reduce transportation system costs. The center's five technical areas, shown in Figure 1, and sample projects within these areas are described in the following sections.

Roadway Maintenance and Construction Technology

Maintaining the quality of highway surfaces and extending the time between pavement rehabilitation projects are major objectives of transportation agencies. Ensuring a safe environment for travelers by maintaining roadway markings and lane delineations is a related and critically important job. Typical maintenance and

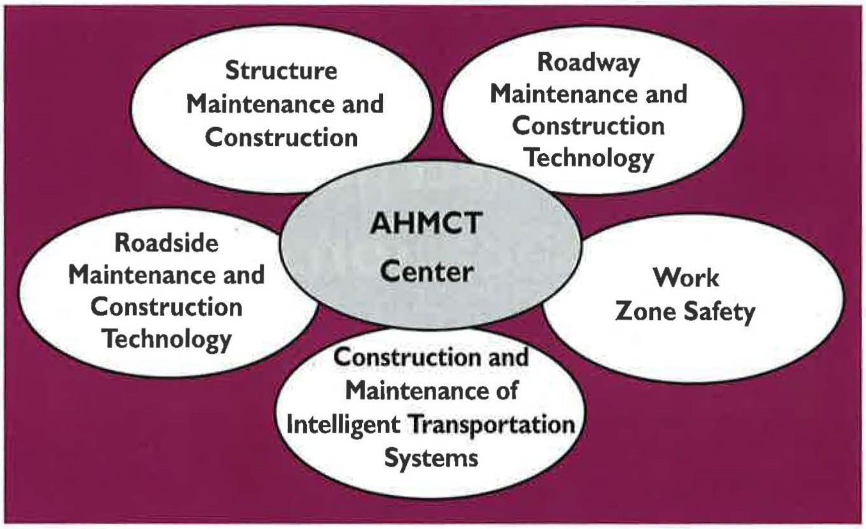

FIGURE 1 Technical areas of the Advanced Highway Maintenance and Construction Technology Center.

construction activities currently being addressed are pavement crack sealing and lane marking.

Automated Crack Sealing Machine

Crack filling and sealing is necessary to ensure roadway structural integrity and extend the time between major rehabilitation efforts. Conventional crack sealing operations can be dangerous and tedious. A typical sealing operation requires a large crew, which seals one to two lane-miles per day while exposed to traffic in adjacent lanes.

Through the support of the Strategic Highway Research Program and Caltrans, the automated crack sealing machine (ACSM) has been developed by UCD and Caltrans with contributions from private industry to improve efficiency, reduce costs, and enhance safety for workers and travelers (2,3).

The ACSM (see Figure 2) is a self-contained prototype vehicle for automatic identification, preparation, and sealing of roadway cracks. It can operate in two modes: sealing cracks entirely within a highway lane or sealing longitudinal cracks along the side of the vehicle. The ACSM's integrated system is completely modular and allows various combinations of subassemblies for sealing procedures that may differ from state to state.

The ACSM includes a three-axle truck with a line scan vision (video) system mounted on the front and a robot positioning system mounted on the rear. Computer systems are housed on the truck bed, as are peripheral support systems. ACSM is driven by various integrated subsystems that

- Detect the position and orientation of pavement cracks at the front of the vehicle,
- Monitor the relative position of the vehicle,
- Integrate all subsystem operations from start to finish,
- Position the crack sealant dispenser and other tooling along the crack,
- Determine the order in which cracks are sealed,
- Verify the presence of cracks, and
- Guide a submachine that seals longitudinal cracks.

The ACSM in a longitudinal sealing mode has been undergoing field testing and can perform longitudinal operations at speeds of more than 16 kilometers per hour. The integrated machine also has demonstrated ability to seal random and transverse cracks. Continued development will simplify its operation and make progress toward commercialization.

FIGURE 2 Automated crack sealing machine.

Robotic System for Roadway Stenciling

The current method used to apply roadway symbols and signs requires manual placement of a stencil on the pavement, followed by either the application of paint or torch-down of a thermoplastic material. Both procedures expose maintenance employees to traffic and possible injury and are slow and labor intensive.

A robotic system for stenciling roadway markings can improve efficiency and worker safety. By using a spray gun guided by a robot manipulator, a single operator will be able to plan the operation on-site, position the vehicle for proper alignment, and complete the stenciling operation from the cab of the maintenance vehicle. The system will paint different sizes of various symbol configurations. System versatility will be obtained through the use of advanced robot path planning methods (4).

Initially this project has focused on painting target marks for photogrammetry, a survey method that uses aerial photographs of the roadway. The target marks are used for the calibration of vertical positions and are currently painted manually by survey crews. A black square is painted for the base image and an X stencil is placed on the base and painted in a contrasting color, usually white. A two-person crew requires two to three days to paint target marks on one mile of highway.

The prototype system (Figure 3) is composed of a gantry robot (*x-y* plotter) and is designed to pass two rows of painting nozzles (one white, one black) over the asphalt surface to complete the photogrammetry mark. Motors and pneumatic cylinders are used to lift the stenciling apparatus from the truck to the ground, thereby eliminating the need for workers to be exposed to traffic.

FIGURE 3 Sign-stenciling robot prototype.

Laser-Guided Lane Striping System

Each year, Caltrans expends some 85 person-years of labor to paint 76,000 kilometers of highway lane stripes. The process is painstaking. The driver must guide the paint vehicle precisely, using multiple sights and mirrors so that outrigger-mounted paint guns follow existing lines. Preoccupied with the task, the driver may not be fully aware of fast-moving and constantly changing traffic conditions. A crew member in the rear of the vehicle selects the striping patterns and triggers the paint guns. Both tasks are tedious and fatiguing.

The AHMCT Center is automating part of the lane striping process to improve efficiency, reduce the impact on traffic flow, and enhance safety. Laser-guided automation of the outrigger guidance system will increase driver awareness of surrounding traffic and reduce fatigue. Automation of the paint gun triggering process will enable the second crew member to perform other tasks. Increased productivity and greater safety will result, and striping accuracy will be ensured.

The system will be able to position the paint gun outrigger and trigger the correct paint nozzles to duplicate existing stripes. It must be able to identify pavement stripes that have degraded by 50 percent, provide accurate guidance response at speeds of up to 64 kilometers per hour, and maintain tracking tolerances of 13 millimeters laterally and 102 millimeters longitudinally.

Roadside Maintenance and Construction Technology

Transportation agencies are also responsible for the maintenance of highway rights-of-way and infrastructure. Necessary tasks include construction of the roadside and the maintenance activities of roadside vegetation control, landscaping, litter and refuse removal, graffiti abatement, and the cleanup of hazardous material spills.

Landscape maintenance research is aimed at reducing the use of water for irrigation and herbicides for vegetation control. Biogenetic technology offers promise for the development of a wide variety of landscape plants that require less maintenance.

Employee exposure to traffic can be reduced through the use of automated litter pickup equipment. Efficient and fast methods for graffiti removal will alleviate personnel requirements significantly while minimizing the use of hazardous cleaning chemicals.

Smart Herbicide Applicator

Vegetation control on transportation system right-of-way is a necessary component of Caltrans' highway maintenance program. Uncontrolled weed growth impedes driver visibility, fuels grass and forest fires, and contributes to pavement degradation. Caltrans uses an integrated system of vegetation control that includes mechanical methods; use of low-growing, drought-tolerant, and fire-resistant plants; and application of herbicides. The development of an intelligent herbicide application system will help Caltrans meet its herbicide reduction objectives and control vegetation that cannot be treated effectively in other ways.

This project is intended to develop a method of herbicide application that targets specific plant materials, avoids others, and applies precisely required amounts of herbicide accurately and without overspray. The system incorporates the following technologies:

- *Vision sensing* is used to detect green plants. The targeted field of view is up to 2.4 meters perpendicular to the traveling vehicle.
- *Image processing* is used to identify and characterize detected plants. Leaf sizes

as small as 1.25 square centimeters can be detected by the vision system. The location and size of a plant can be approximated while the vehicle is in motion. These data are processed by a control system to actuate spray nozzles.

• *Speed-compensated control system* uses data from the image processor and a radar-based speed detector. The ground speed detector is necessary to determine the trajectory of the herbicide and the nozzle action required for targeting. The combination of these data will enable the controller to specify the exact moment to actuate the appropriate applicator nozzle so that the detected plant is targeted.

• *Rapid-response spray nozzles* on a boomless vertical nozzle bank precisely direct the application of herbicides to plant tissue and reduce overspray.

The integrated components have already been demonstrated, and integration into an existing Caltrans vegetation maintenance vehicle is under way. The prototype demonstration system is shown in Figure 4. The intelligent herbicide application system will efficiently operate up to 16 kilometers per hour. Regional vegetation control crews will be involved in the evaluation of the system—a critical step in developing equipment that will be acceptable and usable by the maintenance work force.

FIGURE 4 Smart herbicide applicator prototype.

Caltrans intends to reduce its use of herbicides by 50 percent by the year 2000 and by 80 percent by the year 2012. This project will help to achieve that commitment and reduce highway maintenance costs.

Laser Removal of Graffiti

The marking of noise barriers, signs, buildings, bridges, and other objects is an excessively costly problem for Caltrans and others who maintain public and private property. Such graffiti can create significant hazards by rendering signage unreadable and distracting drivers.

Current methods for graffiti removal include chemical cleaning, repainting, sandblasting, water blasting, or replacing or removing the vandalized object. Workers may be exposed to hazardous chemicals and to traffic during these operations. The task is labor intensive and the methods and chemicals used often damage treated surfaces.

The feasibility of removing graffiti from transportation facilities using laser irradiation is under study at the AHMCT Center. The laser method of removal does not require solvents or other materials nor does it result in environmentally harmful byproducts.

Development of an effective laser graffiti removal system begins by first examining the efficiency of laser wave and pulse lengths on graffiti removal. Each graffiti tag (spray paint, crayon, etc.) and underlying surface (concrete, cinder block, brick, metal, wood) will be considered and the best laser technique for each situation recommended. Researchers will consider various continuous- and switched-wave lasers and frequencies, modulation, and power levels. The project goal is the development of a working prototype. The high demand for a functional product from this project is nationwide. Signs with tags removed by the laser process are shown in Figure 5.

Teleoperated Hazmat System

Caltrans' responsibility in highway maintenance extends to the removal and disposal of unidentified, potentially hazardous substances spilled on roadways. In current practice, emergency response teams attempt to identify spills with binoculars and spotting scopes from a safe, remote site. Occasionally, a spilled container label or placard is within sight, and the substance can be identified and removed quickly. However if the substance is unknown and cannot be positively identified by remote visual inspection, additional procedures and specialists must be employed. Maximum safety procedures must be practiced because fumes from toxic spills can be lethal. Emergency response teams consist of six individuals: two are responsible for obtaining a sample of the spilled substance, two are responsible for decontamination, and two are available for backup.

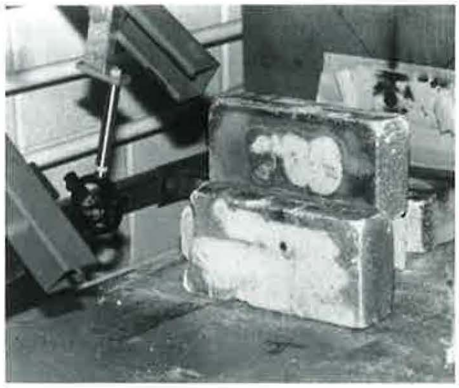

FIGURE 5 Highway sign pieces with tags removed by laser.

Current procedures are time consuming and inherently dangerous to workers and travelers and cause significant traffic delays.

Two prototype hazardous spill sampling vehicles have been developed in conformance with detailed specifications from Caltrans hazardous material coordinators. Both vehicles are remotely controlled and equipped with video monitoring systems for close-range inspection of the spill site. Each vehicle can retrieve samples (solids and liquids) and monitor and record activities during the emergency response operation. Instrumentation aboard each vehicle can report whether contamination is confined or spreading. A teleoperated hazmat vehicle is shown in Figure 6.

Each vehicle is equipped with a full pan-and-tilt video camera. Design specifications require a minimum battery life of

30 minutes, shock-mounted drive wheels, explosion-proof motors, a sealed exterior for ease of decontamination, and the capability of being retrofitted for additional air-monitoring equipment (photo ionization). Through the use of these vehicles, the time to obtain material samples can be reduced to about 15 minutes and protective clothing requirements are reduced to Level C.

The next step in this project is the design of a remote-controlled laboratory, which will receive the samples collected by the vehicles for testing and identification. Key issues in the design include methods for identifying unknown substances, complexity and functionality, and the division of labor between the remotely controlled hazardous material laboratory and its human operator.

Structure Maintenance and Construction

The development of methods and equipment for rapid and remote inspection of bridge components and other structures is critical to maintaining the safe condition of deteriorating transportation infrastructure. The nation's large inventory of aging elevated structures mandates frequent and detailed inspections using equipment of increasing sophistication. Efforts focus on the development of products that will allow remote inspection of structural facilities, reduce human risk, and improve efficiency.

Caltrans bridge inspectors must frequently examine California's highway bridges and other structures to identify fracture-critical cracks before they become safety problems. Conventional methods involve the physical positioning of an inspector by the hydraulic telescoping arm of a "snooper" truck, thus providing visual access to otherwise inaccessible bridge components. The process is time-consuming, dangerous, and may be affected by poor lighting conditions.

A robotic aerial bridge inspection platform is under development that will make bridge inspections safer, faster, more efficient, and less expensive. This unmanned tethered robot platform will fly and inspect critical locations from a ground-based site through the use of a device to enable remote video inspection and computer image enhancement.

The first phase of this project has produced a remote-controlled flying platform (Figure 7) on which the inspection instrumentation can be mounted. The development of a more sophisticated pilot control system is under way. The flying platform is capable of vertical takeoff and landing and will be equipped with a high-resolution video camera. The platform is designed with unique, electrically driven ducted-fan technology. For added safety, there are no exposed moving parts. With this system, the camera can be positioned within 0.6 meters of the critical bridge component.

The aerial system includes a single ducted vehicle with an exterior diameter of 560 millimeters, a height of 580 millimeters, and a weight of approximately 180 Newtons. Electric power is supplied through a 30-meter power cable, providing 300 volts DC to operate two 4.5-kilowatt electric motors. The cable also carries control signals and video images through fiber-optic lines. Each motor drives a set of five fan blades and creates sufficient thrust to lift and control the vehicle and a 90-Newton payload. The vehicle is automatically stabilized through the use of on-board attitude sensors.

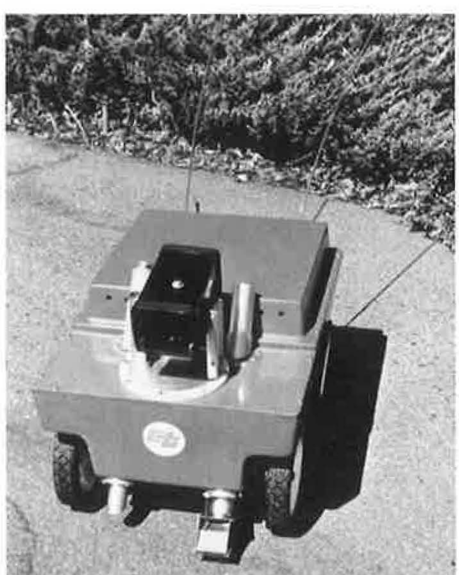

FIGURE 6 Teleoperated hazmat retrieval vehicle.

FIGURE 7 Aerial robotic platform.

The Image Enhancement Ground-Based System (IE-GBS) obtains video signals from a color RS-170 camera mounted on the remote-controlled aerial platform and the video camera can be panned and tilted to see from any angle. The IE-GBS consists of a computer and associated equipment with the capability for real-time display of images received from the inspection camera. The system acquires, stores, and processes images and can highlight specific features so that cracks and structural deformities can be readily identified. The benefits of this project include (*a*) enhanced images that help in locating structure cracks, (*b*) improved safety for inspection crews, and (*c*) image storage for review following inspection.

Other potential applications for the aerial platform and IE-GBS range from power line and building inspection to police surveillance.

Work Zone Safety

Many safety devices and procedures have been developed to protect line and field workers, including protective head gear, brightly colored garments, safety cones, and lane closure procedures. These and other products and procedures have been adopted by the construction industry with life-saving success.

The development of efficient, compact computers and intelligent sensors is leading toward the development of more sophisticated and active life-saving products. These items have the potential to perform such tasks as warning highway workers of the intrusion of traffic into the work zone and the approach of heavy equipment.

Teleoperated and Automated Maintenance Equipment Robotics (TAMER)

The use of heavy equipment such as crawler tractors, dozers, and loaders is crucial to highway maintenance. These machines are used in hazardous operations such as repairing highways after an avalanche, clearing landslides, cleaning up hazardous materials, and clearing snow. In such operations, in which soil and snow banks are unstable, road boundaries unrecognizable, or toxicity of potentially hazardous spills unknown, operators work in a high-risk environment. Teleoperated machines could perform many of these jobs and reduce worker exposure to dangerous conditions.

The objective is to design and construct a teleoperated or remotely controlled system to operate heavy-duty equipment from a remote site. The concept allows normal equipment operation during regular use. Typically the use of remote control has proven effective in removing personnel from potentially hazardous situations at the expense of reduced productivity. The goal is to restore lost productivity and improve efficiency through automation.

A remote-control package for a front-end loader has been developed with the collaboration of a company experienced in both remote vehicle control and secure communication systems. The communication and control system includes a microcontroller-based operator control unit, a full duplex spread spectrum RF modem capable of operation up to 19.3 kilobits per second at a range of up to 488 meters, and an on-vehicle, computer-based control system. The radio remote-control package uses a pair of transceivers to implement two-way communication. Two portable remote stations, a backpack mount and a palletized truck bed mount, have been successfully developed and demonstrated. The prototype system in operation with the truck-based operator station are shown in Figure 8.

FIGURE 8 Teleoperated and automated maintenance equipment robotics operated from backpack-mounted controller.

Tethered Mobile Robot

Many highway maintenance operations currently use materials and tools attached to or supplied from a support vehicle. For example, roadway crack sealing operations require maintenance personnel to apply hot liquid sealant from a dispenser wand. The wand is attached to a vehicle platform supporting equipment that melts the sealant and delivers the material to a dispenser tip. The operation is often slow and inefficient, impedes traffic flow, and exposes workers to potential injury. Other maintenance operations require power tools that depend on remotely located energy sources, such as vehicle-mounted generators, compressors, or engines.

Conventional robots have a comparatively low-load capacity in relation to their weight. Highway maintenance tools (e.g., pavement routers, paint nozzles, and the like) are heavy and exert extreme forces during operation. Furthermore, commercially available conventional robots usually perform repetitive manufacturing tasks, simply moving objects from one location to another. Highway maintenance operations are generally more complex and require tooling to follow paths that do not conform to preset patterns.

Work is being directed toward the development of a wheeled mobile robot system for the requirements of highway maintenance and construction tasks (5). The devices are called tethered mobile robots (TMR) because a tether attaches them to the support vehicle for power and supplies.

A scaled-down prototype TMR has been built to determine mechanical system and control specifications for operational models. Scaled prototype testing has led to the design and fabrication of a full-sized TMR capable of numerous demanding operations such as crack sealant dispensing (see Figure 9). A larger model is under design to accommodate high-load applications such as pavement routing.

A three-wheeled, differentially steered configuration is used to satisfy motion and tracking requirements. Such a configuration is robust and provides necessary tractive force. An instrumented passive mechanical link is used to measure the relative position of the TMR with respect to the support vehicle and to provide a means for material and power delivery. The control architecture is based on the latest mechatronics technology, which allows versatility coupled with rapid system response. The unique aspects of this robot are the control architecture, the relative position measurement system, and its design for high loads.

FIGURE 9 Tethered mobile robot.

Construction and Maintenance of Intelligent Transportation Systems

As transportation agencies implement more technologically advanced transportation systems, construction and maintenance operations will become more complex. Accurate equipment positioning, frequent testing, and rapid repair of control and communication instrumentation will be critical to automated transportation system construction and maintenance. Future maintenance of automated intelligent highways will be performed in an environment that supports more vehicles moving at higher speeds. Recent advances in designs for automated assembly, manufacturability, and life-cycle design justify the evaluation and development of new concepts for automated construction and maintenance of the transportation infrastructure.

Automated highway systems (AHS), often called smart highways or intelligent transportation infrastructure, integrate a variety of communication and control systems to make travel safer and more efficient. An AHS may include computer-driven networks and a complex array of sensors and data transfer systems that create an automated, intelligent relationship between vehicles and the transportation infrastructure. The success of such automated highways depends on development of system architecture (6), operational protocols, and maintenance and construction technology.

The objectives are to identify and analyze issues related to the construction, maintenance, and operation of smart highway systems in California's urban and rural environs. Examined are the human resources and management requirements for automating transportation systems. The research seeks to resolve the following specific AHS maintenance requirements:

- Identify functional components and technologies in a generic AHS configuration,
- Identify existing and evolving maintenance functions and operational requirements for each of the component technologies, and
- Develop an architecture for maintenance and operational functions.

Related tasks are necessary for the automated construction of an AHS and are included in the research program:

- Develop a system architecture for AHS construction,
- Analyze modularity and configuration potential of AHS designs,
- Analyze and evaluate the application of automation and robotic technologies, and
- Develop specifications and requirements for AHS construction.

Acknowledgments

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