# NORTH CAROLINA
# Robotics for Increased Safety in Highway Construction and Maintenance

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A key advantage of robotic technology is the capability to replace humans with machines in dangerous work environments. Three projects in North Carolina demonstrate the way advanced technology can be used to provide operators with "smart" data, remove these employees from a dangerous work environment, and adapt existing equipment for use as platforms for robotic operation. The projects involve crane operations, pavement marker application, and bridge paint removal.

## Using Robotic Technology for Crane Operations

Work crews of the Bridge Maintenance Division of the North Carolina Department of Transportation (NCDOT) must frequently perform maintenance operations that subject equipment to unusual loading conditions. Cranes, the workhorses of bridge maintenance crews, are most affected in these operations. The crews often use cranes to pull debris lodged in bridge piers or extricating piles. In past years, severe accidents involving boom and turret drive gear failures have been recorded. An accident involving the bending of a crane boom was reported recently. The repair of one of these booms can cost as much as $16,000. NCDOT currently supports a research project for the development of protective technologies to secure the department's fleet of 64 truck-mounted cranes. A crane equipped with sensors to measure behavior under various loading conditions is shown in Figure 1.

Two cases of critical loading conditions have been studied. One is the dragging of loads whereby the forces induced through the cable to the crane boom are not in a vertical plane, thus creating additional stresses. Visual inspection of crane booms revealed cable marks that indicate the occurrence of excessive dragging. The second case involves activities that result in abrupt extrication that may occur during the removal of piles, tree trunks, and other objects from the ground. When operators bring the crane into one of these loading conditions, they are operating in uncharted conditions. Allowable boom angles, loading capacities, or boom extensions were not developed with consideration for these types of operations (*1*). Consequently crane operators and foremen are obliged to rely on their perception of the situation to make decisions on the basis of their experience. These decisions have to be made in real time and often with insufficient and inaccurate information to complete a given job.

The foreman, who directs the lifting operation, has no means of predicting the exact mechanical effects (i.e., stress buildup in the boom cross section) produced during these abnormal and uncharted loading cases. Even though the operator can feel the response of the

FIGURE 1 NCDOT's sensor-equipped crane during experimental test.

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crane to these loading conditions to a certain point, the feedback from the machine is too inaccurate for decision making. Many accidents prove this point. Traditional overload protection systems provide a means for preventing damage to the boom but do not consider dragging or extrication cases, and some older cranes lack even these safety devices. The nature of the work and the demand for completing the job force the operator and supervisor to push the equipment to the limit.

### Approach to Safer Crane Operations

To provide the information needed to operate the crane safely, a boom tip model with an anti-two block system was equipped with two types of electronic sensors (Figure 2). The vertically suspended pipe piece is a tip-switch that monitors the cable angle relative to the vertical. Directly attached to the boom tip are two accelerometers that measure acceleration in the vertical and horizontal planes.

A series of experiments has been performed duplicating the two critical loading cases (dragging and extrication) and the vertical lift by using a scaled-down version and a sensor-equipped crane. The sensors include (*a*) accelerometers, (*b*) pressure transducers, (*c*) load cell, (*d*) tip switch, and (*e*) inclinometers. The use of these sensory technologies allowed for the real-time collection of data during the loading experiments. Data on cable force and inclination, boom acceleration, hydraulic pressure, boom angle, boom extension, and crane level have been collected using these sensors.

The results of these experiments served as the basis for the analysis of the behavior of the crane under critical conditions. The data collected from each sensor are analyzed for patterns that are characteristic of each loading case. The establishment of patterns and threshold values representing the safe operation zones are the objectives of this analysis. These electronically recognizable patterns form the basis for the design of the control aid system.

The smart crane control support system presents an approach that keeps the operator involved. Sensory technologies can improve the operator's perception. Data on crane conditions can be collected from the sensors and fed to the microprocessor through an analog-to-digital converter. The microprocessor is programmed to continuously interpret the readings. The operator has the final decision-making power (Figure 3) (2).

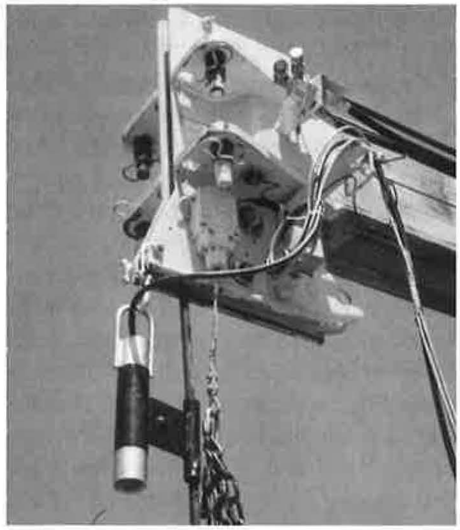

FIGURE 2 Electronic sensors mounted on crane boom tip.

One of the key functions of the microprocessor is to monitor the many sensors and to search for recognizable signal patterns. If the sensor readings during the operation exceed established threshold conditions, the control system can signal a warning message, a screen output suggesting a corrective action, and even the eventual shutdown of the crane.

A written log of crane conditions during the daily operations can be retrieved from the files created automatically by the microprocessor. This capability may have a positive psychological effect on the operator because it can prevent the operator from following inappropriate requests from the work crew.

### Project Status

This system is being readied for field testing and a hierarchical control procedure has been devised. All the electronic devices, cables, power supplies, and the like have been hardened to survive the rough construction environment. Field tests were conducted in December 1994.

## Telerobotic Raised Pavement Marker Applicator

The pavement marker placement process is time-consuming and can be hazardous. In a common scenario, a truck with a specially designed operator bay travels slowly along the road and stops at required intervals [e.g., every 12.2 meters (40 feet)]. An operator applies bitumen to the

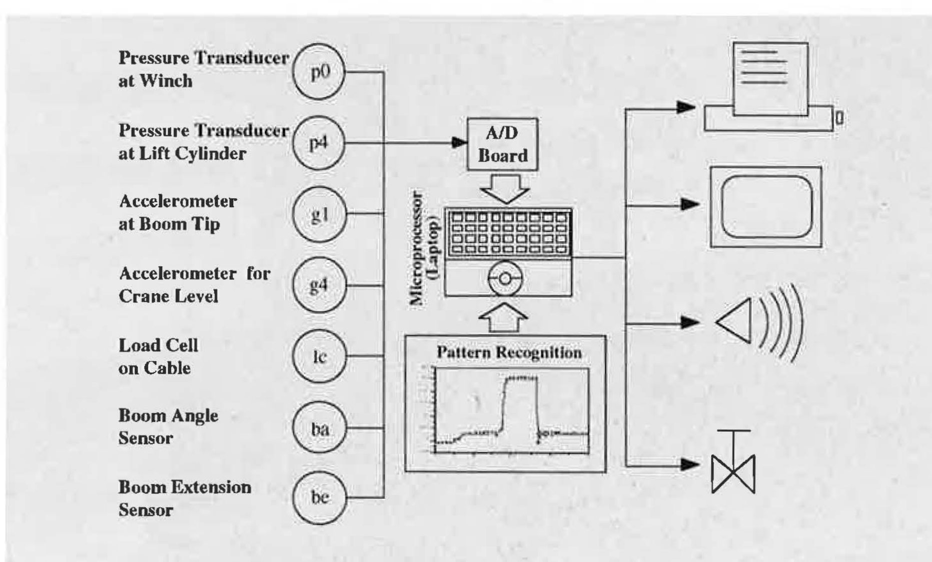


FIGURE 3 Analog control system for safe crane operations.

road via a hand-controlled dispenser and applies the marker on the bitumen by hand. This procedure requires the operator to extend a hand and an arm into oncoming traffic. The bitumen is approximately 400°F when applied, which provides another opportunity for operator injury. In addition the slow-moving truck necessitates lane closure, which represents a hazard for traffic.

Different approaches and technologies have been evaluated by experts from North Carolina State University, NCDOT, and a local contractor. In view of the mission to create practical solutions, the local contractor's current hardware (e.g., marker truck) was chosen for the new system. A critical aspect of this project was to draw from the experience of the contractor to use as a basis for field tests of different prototypes.

A team has been working on developing a telerobotic raised pavement marker applicator (TRPMA) since July 1993. The specific objectives of this project are to (*a*) test and evaluate the technical feasibility of creating a safer work environment for raised pavement marker application and (*b*) demonstrate the capabilities of advanced technologies in the area of highway maintenance and control.

## System Design and Components

Removing the operator from the hazardous work bay is the most important step toward improving worker safety. The space occupied by the operator can be used to assemble an experimental system that is capable of applying the marker automatically. The first operable prototype was recently installed on one of the trucks provided by the local contractor. The TRPMA installed on a marker placement truck is shown in Figure 4. The side of the truck has been removed to allow space for the developed system. Also installed are the bitumen kettle and pump that feed the hot bitumen to the dispenser via a hose. The first two vertical marker stacks, which are pneumatically operated, can be preloaded to serve as a cartridge and may contain markers of various colors. The marker manipulator is moved, via a smart hydraulic cylinder, to the position of bitumen and marker placement. All actuators are controlled by a microprocessor through the use of electronic relays.

Because of the complexity of deciding on the position of each marker, a human-in-the-loop control architecture was chosen. Telerobotics provided an acceptable framework for the situation, in which an operator is physically separated from the equipment. The camera is mounted on the truck's front bumper to provide the operator, now sitting beside the driver, with a view of the marker placement operation (Figure 5).

The key to teleoperation is the interfacing of the camera with the smart cylinder that manipulates the bitumen dispenser. This telerobotic system is composed of a camera, a television monitor in the cabin, and a computer equipped with frame-grabber software and a mouse. While monitoring the operation and using a cursor appearing on the television monitor, the operator uses the mouse to select the position of the next marker. The cylinder then extends to the desired position before the bitumen is sprayed and the marker is placed automatically on top of the bitumen.

The current system requires the truck to stop every time a marker is placed. To eliminate the need for a stop-and-go operation and to increase productivity and traffic safety, a special mounting will be added that holds the marker and accelerates it in the opposite direction from that in which the truck is moving for in-motion marker placement.

**FIGURE 4 Installation of telerobotic raised pavement marker applicator on truck.**

## Robotic Bridge Paint Removal System

Steel girder bridges deteriorate rapidly if they are not properly protected against corrosion. The protection includes paint application for bridge structures to stay in safe condition. Surface preparation is an important step that should be taken before the application of new paint. Preparation is required for removing interference material, increasing surface profiles, and washing away water-soluble salts to ensure the long-term performance of the coating system.

The presence of lead in the old paint coating represents a particular problem because it requires special attention in the removal process. Occupational Safety and Health Administration regulations have recently become more restrictive to protect the health and safety of workers and the


FIGURE 5 Camera mounted for teleoperation.

natural environment of the working area (4). An automated bridge paint removal system appears to be a promising approach that can free workers from hazardous working environments (5). The Robotic Bridge Paint Removal (RBPR) project, sponsored by the Federal Highway Administration, addresses this increasingly urgent problem in bridge maintenance.

### Current Automation in Paint Removal Applications

Although the application of robotics to the painting operation is nothing new, its application to paint removal is a relatively new area. Southwest Research Institute developed an automated robotics system for aircraft paint stripping (5). The system consists of two robots, two robot controllers, a cell control computer, paint sensors, and bead blasting equipment. Various sensors are used to detect the availability of blasting materials, clearance of objects, location of the end point, and removal rate of blasting. Using the data input from the sensors, the robotic system controls the speed of the robot arms to ensure uniform cleanup regardless of the thickness of existing paint coatings.

Another automated blast system, called Auto Blaster, was manufactured by D&S Services, Inc. (6). This system, is a hoisted platform type and is operated either in an automatic or manual mode using wireless controllers. After blasting is finished, workers can do a final touch-up while standing on the platform.

Although not designed specifically for bridge paint removal work, LTC, Inc., developed an actuated system that is pneumatically powered. Movement is controlled in both vertical and horizontal directions by fingertip manipulation. The ease of control relieves workers of loading required for manually handling blast hoses. Valley Systems, Inc., has built an automated paint removal system based on a water jet technology. The approach takes advantage of a platform deck that is suspended by two cables on the flat surface of a large storage tank (4).

### Design and Development of Robotic Bridge Paint Removal System

With a grant from FHWA and strong cooperation and support from NCDOT, a prototype RBPR system has been designed, built, and tested. One of the key advantages of this project was the adaptation of an existing bridge maintenance crane instead of the development of a new system. Retrofitting existing equipment could reduce system development costs and time and ensure economically acceptable solutions. The unique shape of bridge beams and the need for dust and debris control provided challenging design problems and required innovative solutions.

A schematic overview of the end-effector components in the RBPR system is shown in Figure 6. The selected system is composed of (*a*) a bridge inspection crane, (*b*) an actuated platform, (c) two sliding tables, (*d*) a robot arm, (*e*) a dust control mechanism, and (*f*) a sandblasting and vacuuming system. The third section of the crane boom was replaced for retrofitting. The actuated platform with the two sliding tables was built for positioning the robotic sand blast and dust control mechanisms.

Each element of the RBPR system is activated in sequential order to perform given tasks such as positioning of the platform end effector, spot cleaning of corroded steel beam surfaces, and containment of dust and debris. Control of the RBPR system is done by a vision system made up of a camera, a television monitor, and a frame grabber. Ultrasonic sensors provide distance data that are used for avoiding collision with any object under the bridge deck.

### Preliminary Field Test

During the development of the RBPR system, several preliminary tests were conducted on a steel girder bridge to review

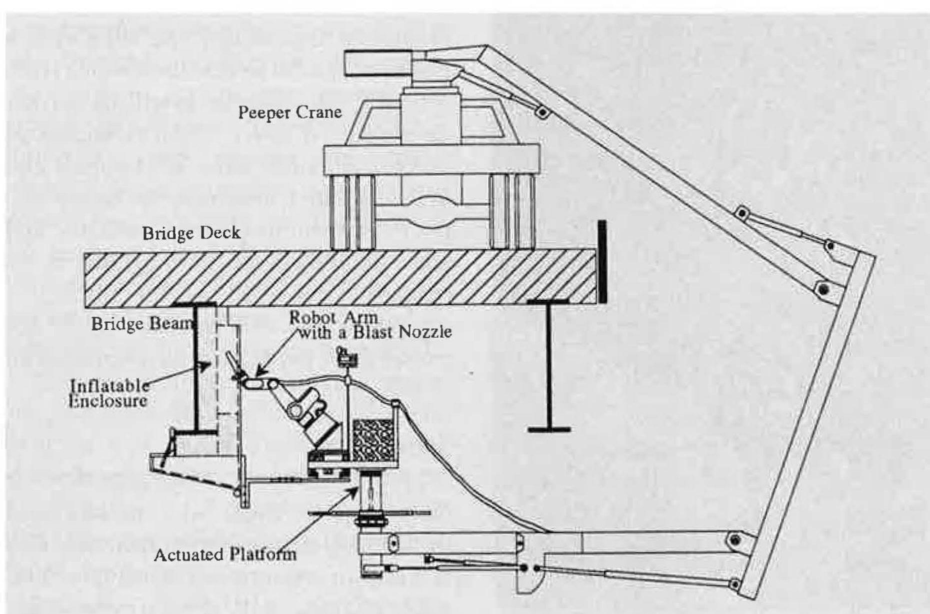


FIGURE 6 Overall view of Robotic Bridge Paint Removal system.

FIGURE 7 Deployment of Robotic Bridge Paint Removal system for field testing.

the feasibility of the conceptual design (Figure 7). The tests included containment of blast dust, actuation of end-effector components, and verification of the computer-integrated control architecture. These experiments demonstrated that vision-based telerobotic blasting is effective in the spot cleaning of corroded paint and that the enclosure mechanism can satisfactorily collect abrasive blast material. The prototype end-effector system is shown in action in Figure 8.

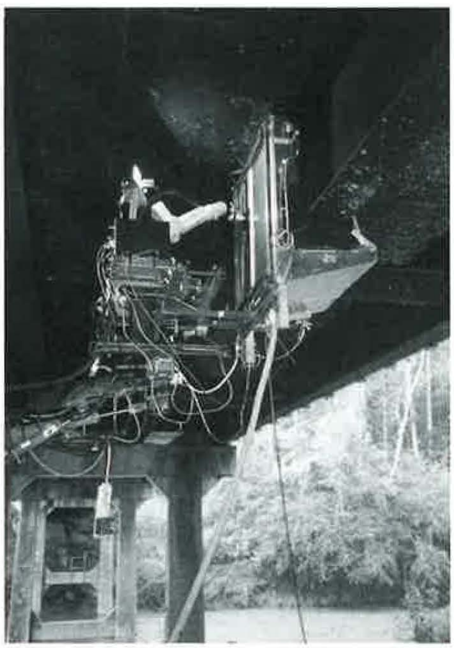

FIGURE 8 End effector in action under bridge deck.

## Future Work

Because of its flexibility, the RBPR system can be expanded to execute various types of tasks. For example it will be further developed to cover different shapes of bridge structures such as channels and bracings. The system can also be retrofitted to perform inspection, washing, and spray painting. Such an integrated maintenance system will provide alternative solutions that will increase safety for workers, the public, and the environment.

## Summary

New projects under way include field demonstration of a robotic excavator that is linked in real time to a spatial positioning system that will provide an interface with computer-aided design data. Another method that reduces the danger of hitting buried utilities during excavation and trenching is being researched. Close partnerships among academia, government, and industry are central to all the reported projects.

## Acknowledgments

The TRPMA project was funded by NCDOT and its support is gratefully acknowledged. Also recognized is the assistance of Clark Pavement Marking, Inc., and the Instrument Shop of the Engineering Research Service Department at North Carolina State University. The combined expertise of the many participants was instrumental in moving the project ahead. The authors believe that such coordination between the system designer and the end user can significantly reduce project time and costs while ensuring the practicality of the result. The contribution of Daniel Bernd, an undergraduate student, is also recognized.

The RBPR project is supported by FHWA as a part of an Advanced Highway Research contract. Special thanks are due to Charles Woo of the FHWA Turner-Fairbank Highway Research Center, Jimmy Lee and Fred Mehfar of the NCDOT Bridge Maintenance Division, John Burns of the NCDOT Equipment and Inventory Control Division, and William Medford of the NCDOT Materials and Tests Unit. Also acknowledged are the many individuals at the NCDOT Equipment Maintenance Shop in their efforts to fabricate the RBPR system and Von Luhman, a graduate student in CARL, for his assistance in this project.

The Intelligent Control Aid for Safe Crane Operations project is funded by NCDOT and the expertise of the engineers from the NCDOT Divisions of Bridge Maintenance and Equipment/Inventory Control previously mentioned is acknowledged. Jerry Bagwell from the NCDOT Equipment Maintenance Shop contributed his knowledge of crane operation and maintenance to the project. Yong Bai, a graduate student in civil engineering at North Carolina State University, provided valuable programming services.

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# TRB HIGHLIGHTS

## Cooperative Research Programs News

### Transit Cooperative Research Program

**Impact of Radio Frequency Refarming on Transit Communications**

The Federal Communications Commission has decided to use "refarming" to help mitigate radio frequency congestion and increase spectrum efficiency in the private land mobile radio bands (frequencies below 512 megahertz). Refarming is the reduction in bandwidth allocated to radio channels in the designated bands. Base stations and mobile radios operating within these bands will be obsolete if they are unable to operate in the reduced bandwidth. The refarming of frequencies is likely to have a significant impact on transit communications systems and capital procurement of communications equipment in the future.

Arthur D. Little, Inc., has been awarded a one-year $119,728 contract (TCRP Project C-5, fiscal year 1994) to define the scope of the planned FCC changes as they relate to the transit industry and to characterize and assess the impacts on the industry.

*For further information, contact Christopher Jenks, TRB (telephone 202-334-3502).*

**Tools for Transit Risk-Exposure Identification and Treatment for Bus Systems**

Identification of risk exposure is the cornerstone of the risk-management process because the other elements of risk management rest on the accuracy and completeness of this process. Public bus transit systems have not developed a uniform or systematic methodology to analyze property and casualty exposures, and the effectiveness of the approaches currently used is unknown. For bus transit systems with limited resources and risk-management expertise, a user-friendly methodology for identifying and priority ranking risk exposures is essential to control potential loss.

The Risk Management Center, Inc., has been awarded an 18-month, $194,964 contract (TCRP Project G-3, fiscal year 1994) to (*a*) design tools with which bus transit and paratransit systems can identify exposures to loss, assess risk within their systems, evaluate their loss-control programs against best practices, and make informed decisions about financing risk and (*b*) develop guidelines to collect, categorize, and disseminate loss data that are consistent and compatible among systems.

*For further information, contact Christopher Jenks, TRB (telephone 202-334-3502).*

**Rail-Corrugation Mitigation in Transit**

Rail corrugation is a serious and costly problem for many rail transit agencies. Research is needed to provide a better understanding of the rail-corrugation initiation and growth process; to establish the influence of track, vehicle, and operating characteristics on rail-corrugation development; and to develop suitable means for reducing rail corrugation. This research will yield economic advantages through the reduction of maintenance needs and provide other economic and environmental benefits.

The Association of American Railroads has been awarded an 18-month, $499,691 contract (TCRP Project D-1, fiscal year 1993) to (*a*) develop methods to reduce or eliminate rail corrugation through the identification and use or adoption of compatible vehicle and track components and (*b*) provide guidelines that can be used by transit agencies to reduce or eliminate rail-corrugation occurrences.

*For further information, contact Amir Hanna, TRB (telephone 202-334-1892).*

### 30-Year Anniversary

PENNOCK

**James Scott, Transportation Planner, recently marked his 30-year anniversary with the Transportation Research Board.**

**Robotics in North Carolina**
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