U.S.Department
of Transportation
**Federal Highway
Administration**

Robotic Bridge Paint Removal: Field Testing and Evaluation of Promising Technologies

FOREWORD

This report, "Robotic Bridge Paint Removal Field Testing And Evaluation of Promising Technologies," presents the results of research conducted for the Federal Highway Administration, Office of Advanced Research under a 1993 grant agreement with the North Carolina State University at Raleigh, North Carolina.

The research concerns the feasibility of developing a robotic system to remove bridge paint and contain the dust and residue. The system would result in the removal of workers from this hazardous operation and prevent the dust and residue from polluting the environment.

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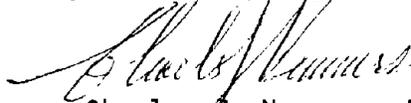
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16. Abstract

Periodic paint removal and re-application is necessary to protect steel girder bridges against corrosion. The paint removal operation for bridge maintenance, however, is hazardous to the workers involved in the process and the natural environment. A particular problem is that certain types of paint used on bridges in the past contain toxic lead. The Robotic Bridge Paint Removal (RBPR) project was initiated under a grant agreement with Federal Highway Administration (FHWA) to study the important factors related to the robotic paint removal process. During the design and development, the unique shape of the bridge beam and the requirement for dust and debris containment caused many problems. These problems, in turn, provided challenges to produce innovative solutions. The robotic paradigm was identified as an especially effective approach for spot cleaning corroded paint on bridge structures. A vision-based computer control architecture was developed that provides the adaptive remote control capabilities for the spot cleaning process. Field tests were conducted throughout the project to evaluate design concepts, identify areas that could be improved, and demonstrate the final working prototype. The results of these demonstrations indicate the application of the robotic paradigm to bridge paint removal has real potential to: 1) improve workers' safety, 2) protect the natural environment during the paint removal process, and 3) minimize the risks to the general public. This project would not have been possible without the close partnership between the North Carolina State University Construction Automation and Robotics laboratory (CARL) and the North Carolina Department of Transportation (NC DOT). The NC DOT not only loaned many of the key hardware components to the project, they also participated in re-configuring, upgrading and field testing the new system.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³

NOTE: Volumes greater than 1000 l shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1. INTRODUCTION

Steel girder bridges rapidly deteriorate if they are not properly protected against corrosion. Over time, periodical paint removal and re-application becomes necessary to maintain the corrosion protection and ensure the steel structures maintain their integrity. However, the paint removal process for bridge maintenance is often hazardous to the working personnel and the environment. A particular problem is that certain types of paints used in the past on steel girder bridges contain toxic lead.

Recently, the Occupational Safety and Health Administration (OSHA) has issued very restrictive regulations to protect both workers and the environment from lead exposure. (Kapsanis 1993) To communicate the criticality of the problem, OSHA assesses high fines when contractors violate lead exposure and contamination standards. (ENR 1994) A robotic paint removal system promises to address OSHA's concerns by removing the workers from the hazardous working conditions while protecting the natural environment.

The Robotic Bridge Paint Removal (RBPR) program was initiated under contract with the Federal Highway Administration (FHWA) in order to investigate the applicability and critical issues of using robotic systems in the paint removal process. The RBPR program was to culminate with a field demonstration of a working prototype RBPR system. During the period from July 1993 to September 1994, the Construction Automation and Robotics Laboratory (CARL) at North Carolina State University (NCSU), in close partnership with the North Carolina Department of Transportation (NC DOT), designed, developed, constructed and tested the prototype RBPR system.

Robotizing the paint removal process offered many challenges during the design and development of the RBPR system. As an example, the unique shape of bridge beams required innovative hardware systems to provide the necessary robotic control features and the proper interfaces between the robotic system and the bridge structure. The sequential control tasks of robotic bridge paint removal necessitated a computer-integrated control system architecture to provide the RBPR system with the necessary flexibility. This conclusion was reached after a number of brainstorming sessions were held with experts from NC DOT and private companies.

The RBPR system was tested over the course of the design and development process to acquire the necessary criteria for establishing final design parameters and to demonstrate the potential applications of the prototype. Throughout the program, the design concept was validated and design modifications were made as necessary. The final design is a flexible and adaptable RBPR system that can efficiently deal with the dynamic task environment found under the bridge deck.

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2. BASICS OF THE BRIDGE PAINT REMOVAL PROCESS

SURFACE PREPARATION

Surface preparation has to precede the application of new paint to ensure the long-term performance of the coating system. The preparation includes removal of old coating materials, removal of water-soluble salts, cleaning, etc. According to Hare (1990), the three principal goals of surface preparation are:

1. Normalize the surface condition as close as possible to the theoretical condition that a paint coating system is designed for.
2. Ensure the adhesion of coating materials to the steel surface by removing all loose paint, foreign materials, chloride and sulphate ions, etc.
3. Improve adhesion through chemical reactions between the primer and the steel surface by increasing actual surface areas.

In order to prevent health, safety and environmental hazards, careful process planning and control is required. (Medford 1992) The Steel Structures Painting Council has published guidelines and manuals as to the proper paint removal operation. (1988a, 1988b, 1989, 1991 & 1992) They detail proper procedures for coating removal, debris collection, containment enclosures and air ventilation methods.

PAINT REMOVAL TECHNOLOGIES

Paint removal methods most widely used in field operations are: 1) abrasive blast cleaning, 2) vacuum blast cleaning and 3) power tool cleaning. Abrasive blast cleaning uses blast materials such as sands, steel grits or plastic sponges that are air-ejected through a venturi nozzle onto steel surfaces. Vacuum blast cleaning also uses abrasive materials. However, in vacuum blast cleaning the nozzle is surrounded by a skirted chamber that recovers the spent abrasive material and paint debris in a vacuum system. Power tool cleaning systems use power tools such as needle guns or heavy-duty roto peens for removing old paint. The productivity of the power tool techniques is usually low compared to the abrasive blast techniques.

Other paint removal techniques are available. Laser paint removal is a newly emerging technology that appears to be well suited for a robotics approach. Presently, however, the cost of laser systems prohibit their use. Chemical paint removal methods are also available. These are not applicable to bridge paint removal, however, as they do not increase the roughness of the steel beam surface. For paint removal on bridges, the appropriate paint removal system should be selected based on an evaluation of various factors including: the degree of rusting, the purpose of blast cleaning, and the desired type of surface finish. (SSPC 1982)

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RIGGING AND CONTAINMENT METHODS

Because of the elevated location of the work envelope, a rigging system is required to provide safe access to steel beams under the bridge deck and to support productive operations. Also, mechanisms are needed to provide support for dust control systems that collect blast materials and paint debris. The most widely used rigging systems are: 1) suspended staging decks, 2) hydraulic cranes, 3) scissor lifters, and 4) scaffoldings.

The suspended staging deck is supported from the flanges of bridge beams and can be moved along the beams. Dust and blast materials are contained via a plastic enclosure around the deck. Commonly used hydraulic cranes are the "Snooper" or "Peeper" after the manufacturer's brand names. Buckets in which workers ride to perform bridge inspection, paint removal and paint application tasks are attached to the end of the crane booms. The scissor lifter uses an extendable device to provide access to bridge beams from under the bridge. For small bridge structures, fixed scaffolds are preferred. In scaffold applications plastic shrouds are installed to collect blast debris and to protect the natural environment.

STATE-OF-THE-ART IN AUTOMATED PAINT REMOVAL

Although the application of robotics to the painting process is not new, its application to the paint removal process is relatively new. (Robotics Today 1990; Terauch et al. 1993, Daiely et al. 1993) In 1990, the Southwest Research Institute developed an automated robotics system for aircraft paint stripping. (Sturdivant and Weniger 1990) This system consists of two robots, two robot controllers, a cell control computer, paint sensors and bead blasting equipment. The system employs various sensors to detect the availability of blasting materials, the clearance of objects within the work envelope, and the removal rate of blasting. The data input from the sensors is then used to adaptively control the speed of the robot arms to ensure uniform cleaning of existing paint coatings.

Another automated blast system, called Auto Blaster, has been manufactured by D&S Services, Inc. (Journal of Protective Coatings and Linings 1993) The system is operated either in an automatic or manual mode using wireless control. After blasting is finished, workers carrying the necessary blasting equipment can perform final touch-ups by standing on a hoisted platform.

Although not designed specifically for bridge paint removal work, LTC, Inc. developed a remotely operated blasting system. Movement of the blast delivery system is controlled in both the vertical and horizontal directions by fingertip manipulation. The ease of control relieves the workers from manual handling of the blasting hose. Also, Valley Systems, Inc. has built a water jet technology-based automated paint removal system. This approach takes advantage of a platform deck that is suspended by two cables from the flat surfaces of a large storage tank. (Cignatta 1993)

3. THE DESIGN AND DEVELOPMENT PROCESS

PARTNERSHIP-A KEY TO SUCCESS

A close partnership between CARL and NC DOT was instrumental in driving the RBPR project on a fast-track and maximizing the effectiveness of each participant's resources. The close partnership between two or more parties means making long-term commitments with mutual goals to achieve success. (CII 1991) In the RBPR project, cooperation in addressing issues relative to lead paint removal and the comprehensive mix of expertise committed to the project goal were keys to success.

Meetings were held throughout the project period each time important decisions had to be made. The participants included, besides researchers from CARL, members from the NC DOT's Bridge Maintenance and Equipment Control Division. The continual participation of engineers, technicians, operators and mechanics drastically reduced design and fabrication time for the RBPR system.

Brainstorming sessions were used to identify and develop solutions to the various challenges encountered throughout the project. In these sessions, everybody was encouraged to make any suggestions relative to the task at hand regardless of their feasibility. The proposed ideas were then studied and evaluated by the CARL group at a later time. This approach provided the necessary setting for the free, uninterrupted exchange of innovative concepts and ideas. Many initial ideas went through several cycles of refinement such as 3D modeling, shop modifications, fabrications and field testing. Designs were purposely kept flexible to provide a robust system that could easily be modified.

The team work approach was also important in identifying real problems that may be encountered during an actual bridge paint removal operation. Inputs from the field and the equipment shop provided the necessary links to close the gap between the laboratory theory and the practical field application (figure 1).

Figure 1. Members of the project team working at the NC DOT machine shop.

EVALUATION CRITERIA AND SELECTION OF A PAINT REMOVAL TECHNOLOGY

As discussed in the previous chapters, the primary goal of the RBPR project was not to identify and develop an optimal paint removal technology but to use an existing paint removal technology as a tool in a robotic paint removal scheme. To select an appropriate paint removal system for robotic applications, the project team eventually settled on a set of six performance criteria that considered a variety of different issues. These criteria include: 1) ease of debris and dust control, 2) adaptability to different structural shapes, 3) paint removal rate, 4) obtainable cleanness, 5) control of noise level, and 6) space requirement on the bridge deck. Weights were given to each criterion according to their importance (table 1).

As table 1 illustrates, several paint removal methods were considered for robotic application. The matrix shown in table 1 was developed using the established evaluation criteria. As can be seen, the sand blast ranked the highest in the evaluation followed by the shot and plastic abrasive blast methods. For this project, the sand blast method was used because of its high performance and availability. Although the needle gun could be used for areas where the sand or shot blast is not effective, the robotic control of the needle gun poses difficult problems in manipulation.

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Table 1. Evaluation of primary paint removal techniques.

Performance Measures	Wt (%)	Plastic Abrasive Blast	Sand Blast	Shot Blast	Vacuum Blast	Power Tool (Needle Gun)
Ease of Debris/ DustControl	10	1	1	1	4	4
Adaptability to Different Bridge Structures	15	5	5	5	3	4
Paint Removal Rate	20	4	5	5	3	2
Obtainable Cleanness (to Specification)	25	5	5	5	3	3
Control of Noise Level	10	4	3	2	4	1
Space Requirement on Bridge Decks	20	3	3	3	5	5
Sum	100	3.90	4.00	3.90	3.60	3.25

Note: Level of Performance: 5 --- Very Good; 4 --- Good; 3 --- Moderate; 2 --- Poor; 1 --- Very Poor

4. CRITICAL SYSTEM COMPONENTS

The RBPR system, like most other complex systems, is based on a set of integrated subsystems that are often referred to as critical components. These subsystems include: 1) Peeper crane truck with three crane boom sections, 2) actuated platform, 3) robotic abrasive blasting system, 4) containment box with a vacuum pump, and 5) vision system and ultrasonic sensors. Figure 2 provides a graphical overview of the system components. The following sections provide brief descriptions of these five critical system components.
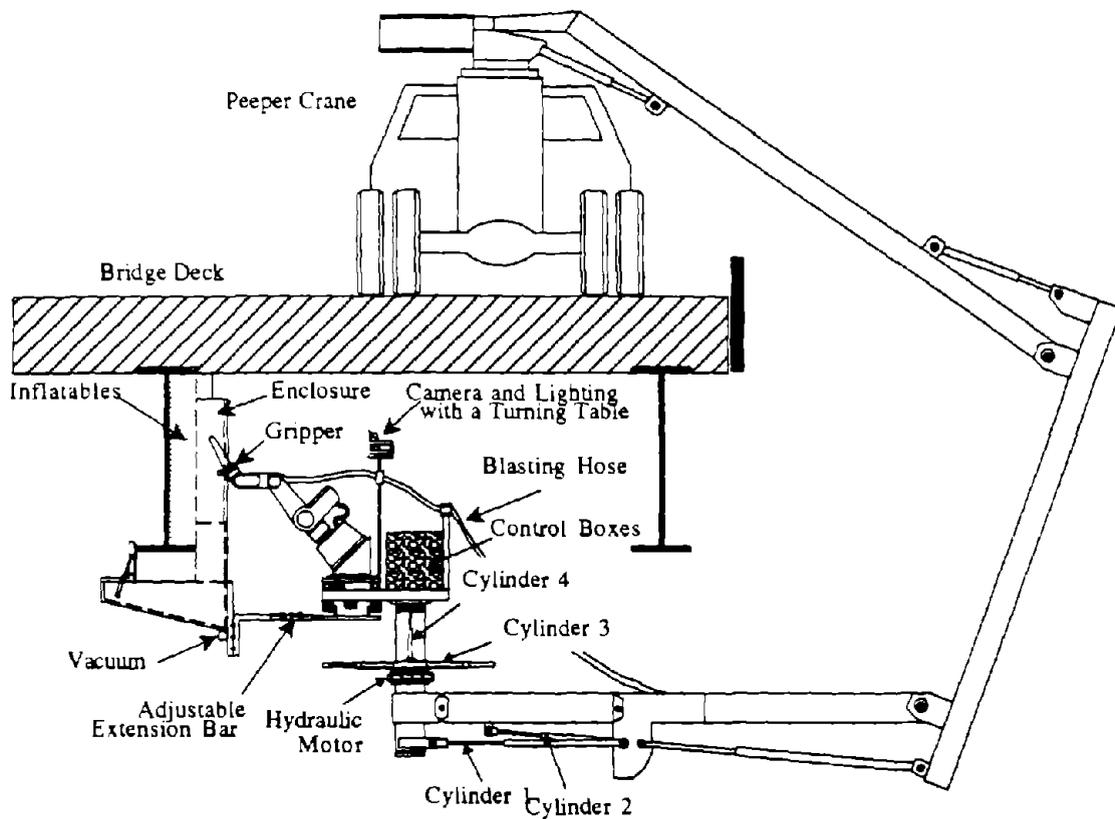

Figure 2. Overall view of the RBPR system design.

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RETROFITTED PEEPER CRANE TRUCK

An existing Peeper crane was retrofitted as a test bed for the RBPR system. As Figure 3 shows, the Peeper crane is a medium-size bridge maintenance truck designed for bridge repair, inspection and cleaning. It is equipped with three boom sections, two baskets and one outrigger. With proper modifications, the crane can be used safely on super elevations with grades of up to 5 percent. With the outrigger properly set up, it is possible to extend the boom away from the centerline of the truck and to maneuver the baskets under the bridge deck.

The crane boom consists of three boom sections and one rotation base to provide four degrees of freedom. Three hydraulic cylinders are used for operating the boom in the vertical plane and one hydraulic motor for rotating the base. The hydraulic system is of an open center type. This permits continuous fluid flow from the pump, through the valves and back to the reservoir when all of the controls are in the neutral position. When a control valve is actuated, the free flow is interrupted and fluid is directed to the desired cylinder or motor.
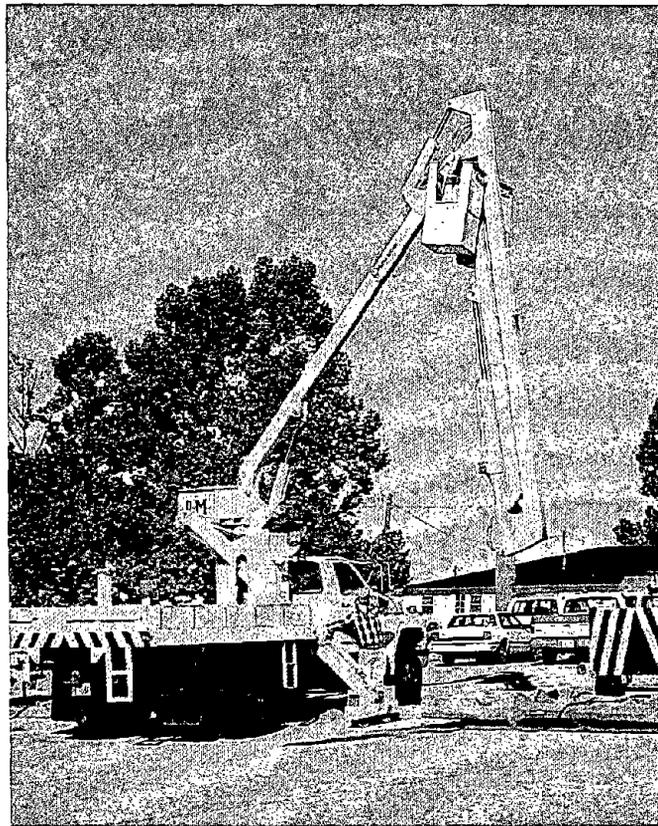

Figure 3. Peeper crane before retroffiting.

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ACTUATED PLATFORM

The third section of the crane boom was replaced with a new boom section and then modified to allow for the installation of the actuated platform. The actuated platform was designed and built to flexibly position the robot arm and the enclosure within the work envelope under the bridge deck. Four hydraulic cylinders and one hydraulic motor provide four degrees of freedom: 1) up/down, 2) linear forward/reverse, 3) rotation, and 4) tilt. The platform can be rotated 180 degrees in order to cover both sides of the bridge beam.

ROBOTIC BLASTING SYSTEM

A Mitsubishi micro robot is used for manipulating the blast nozzle. The robot arm is an articulated joint robot that consists of a base, a shoulder, an elbow, a wrist pitch, and a wrist roll. The robot manipulates a sand blasting system that uses an 8 mm (5/16 in) venturi nozzle and 19 mm (3/4 in) blasting hose. The robot is mounted on a linear sliding table that is controlled via a stepper motor.

CONTAINMENT BOX

The containment box is designed to create a confined area so that paint debris and blast media are captured within the enclosure and can be removed by vacuuming. An inflatable tube provides adaptability to changing structural profiles within a certain range and serves as a damper against traffic shocks and vibration occurring on bridge beams. A second sliding table, powered by a stepper motor, is used for positioning the containment box. Using two separate sliding tables for the robot arm and the enclosure allows the two control identities to move independent of each other.

VISION SYSTEM AND SENSORS

A video camera with a closed-circuit TV monitor is used to aid in the manual operation of the robot arm and the visual inspection of surface conditions both before and after blast cleaning. The camera also permits videotaping the blast cleaning operation for documentation purposes. Ultrasonic sensors are used to measure the distances between the enclosure and the bridge beam surface to provide guidance during final deployment of the end-effector.

The RBPR system is designed to be flexible to accommodate different beam conditions. Development of the total system is accomplished by integrating the various mechanical and electrical components. The following section of the paper discusses the control system architecture that was developed for providing an adaptive control environment for the RBPR system.

5. CONTROL SYSTEM ARCHITECTURE

The development of the control system architecture was based on a breakdown of the control system into individual modules to fulfill the sequential control requirements of automated paint removal. Modularization permits the decomposition of the control system into relatively simple modules with well defined functions. (McCain et al. 1991) The main challenge in developing a control architecture for the RBPR system was the interfacing of the many system modules into a cohesive framework. The complexity of the task required the development of a structure that could then be used in the development of the control software.

OPERATIONAL BREAKDOWN

One important structure used in the development of the control system architecture was the sequential nature of the paint removal task. The following list of eight tasks represents a general breakdown of the operation that is required for efficient deployment of the end-effector and remotely controlled spot cleaning.

1. Setup of the Peeper crane truck.
2. Deployment of the crane boom with three hydraulic cylinders and one hydraulic motor.
3. Positioning of the platform with four hydraulic cylinders and one hydraulic motor.
4. Pre-Inspection of the bridge beam with the camera to identify the spots to be cleaned.
5. Positioning of the containment box with a sliding table and inflating the inflatable tube.
6. Path and motion planning for the robot arm.
7. Blasting of the corroded beam surface.
8. Post-Inspection of the cleaned surface of the bridge beam.

Since the tasks are sequential and repetitive, the system components needed for one particular task can be scheduled and prepared sequentially as well. Each task transition reflects a sequential transformation of the initial control stage to the other stage. The control of the sequence, which is simple in detail, becomes complex in the overall control chain based on the type of functions to be performed. (Bernold and Abraham)

Table 2 presents a further breakdown of the eight levels of tasks into actions and components. It also shows a logic flow diagram that depicts the cyclic nature of the operation.

Table 2. The cyclic procedure of the RBPR.

Sequence	Tasks	System Components	Actions
No / Yes — Stop — Are all cycles on the bridge beam completed? — No — Yes — Are both left & right sides completed? — No — Yes — Is Inspection O.K.?	Setup of Peeper Crane	Crane Truck	Drive to the next blast section.
	Deployment of Crane Boom	Joy Sticks	Control hydraulic cylinders.
		Camera & TV/ Sensors	Identify obstacles on the path.
	Position Platform	Joy Sticks	Control hydraulic cylinders.
		Camera & TV/ Sensors	Identify positions of the containment box.
	Move Enclosure to Right or Left	Enclosure Linear Table	Move enclosure to left or right.
	Pre -Inspect Bridge Beam	Robot Linear Table	Orient camera for inspection.
		Camera & TV	Locate corroded area on the beam.
	Plan Robot Path	Cursor/ Frame Grabber	Get coordinates of the corroded area.
		Automatic Path Planner	Automatically create robot path.
	Position Enclosure & Robot Arm	Enclosure Linear Table	Move the enclosure to blast areas.
		Robot Linear Table	Move the robot arm to blast areas.
	Blast Clean/ Vacuum	Nozzle/ Air Compressor	Blast off corroded paint.
		Vacuuming Orifice/ Air Compressor	Vacuum paint debris and blast dust
	Post-Inspect Bridge Beam	Robot Linear Table	Move camera for inspection.
		Camera & TV	Check cleaned conditions.

FUNCTIONS OF THE CONTROL ARCHITECTURE

The control architecture for the RBPR system is designed to provide high performance capabilities at each level of control. For example, the overall control system should possess a functional capability to effectively support the robotic paint removal process while ensuring that paint debris and blast material are properly collected. Although any real-time controller has unique requirements depending on the complexity of the problem to be solved and the desired goals to be achieved, the control architecture of the RBPR system was designed to support five functional modules, as defined by Olsson and Pianni, for a human in the overall control loop. (1992) These five functional modules are 1) monitoring, 2) interpretation, 3) automatic actuation, 4) remote control, and 5) human operator supervision (figure 4).
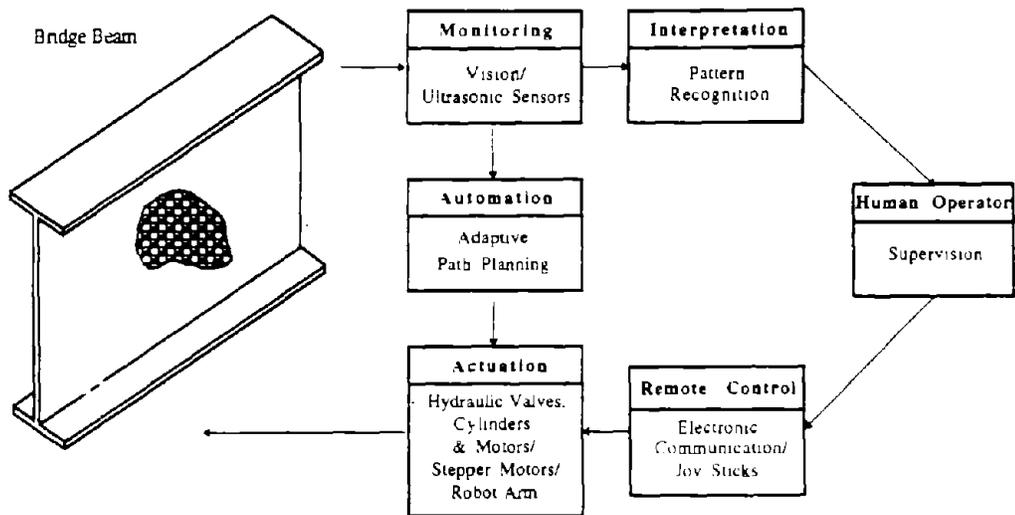
Figure 4. Functions of the control architecture.

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The monitoring module keeps track of the current position of the system components and evaluates the actual behavior of the system using available sensors. These sensors provide distance measurements that indicate the horizontal and vertical alignment of the crane boom and the articulated platform. The video system of the camera and the closed-circuit TV monitor show the actual conditions under the bridge deck and are integrated with a frame grabber to allow for vision-based control.

The interpretation module analyzes sensory data to provide the controller with processed information for reliable decision making. Pattern recognition algorithms are employed to evaluate the feedback data and to define the current status of the RBPR system. Accurate tracking of the system components is needed to efficiently execute required tasks.

The automation/actuation module provides an automatic actuation to the RBPR system that includes automatic positioning of the articulated platform and autonomous spot cleaning by the robot arm. Mechanical components of the RBPR system interface with a computer controller and electronic devices; such as analog to digital converters, an electronic timer, and electrical valves, that interpret input data and make decisions as to the strategy of motion control.

The remote control module links the control station with the actual working environment. In the case of bridge paint removal the station is located on the bridge deck while the paint removal operation is performed under the bridge deck. The remote control mode is a critical element in the automated paint removal process because the mode establishes a means to position the human operator in a safe location away from the hazardous blasting area. In the RBPR system, a computer key board, joysticks, and radio controllers are used for maneuvering the actuators.

The human-in-the-loop control architecture leaves overall control responsibilities to the operator. Even in an automated system, such a supervisory control is still needed because of the complexity of the process. This mode is particularly necessary in the stage of system development and field experiment.

INTEGRATION OF CONTROL MODULES

As previously mentioned, the purpose of the control architecture is to allow the integration of many control modules into a common control framework. The control architecture for the RBPR system resulted in a mechatronic frame that contains a wide variety of mechanical components, electrical devices, an entire robotic manipulator, and computer hardware and software.

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A wide array of methods are incorporated into the modularized control frame for initiating physical motion. These range from simple electronic solenoid relays connected to on/off valves to sophisticated stepper motors that enable the robot arm or the enclosure box to travel at a preset speed on linear motion tables. The individual control modules designed for the RBPR system are presented in figure 5.
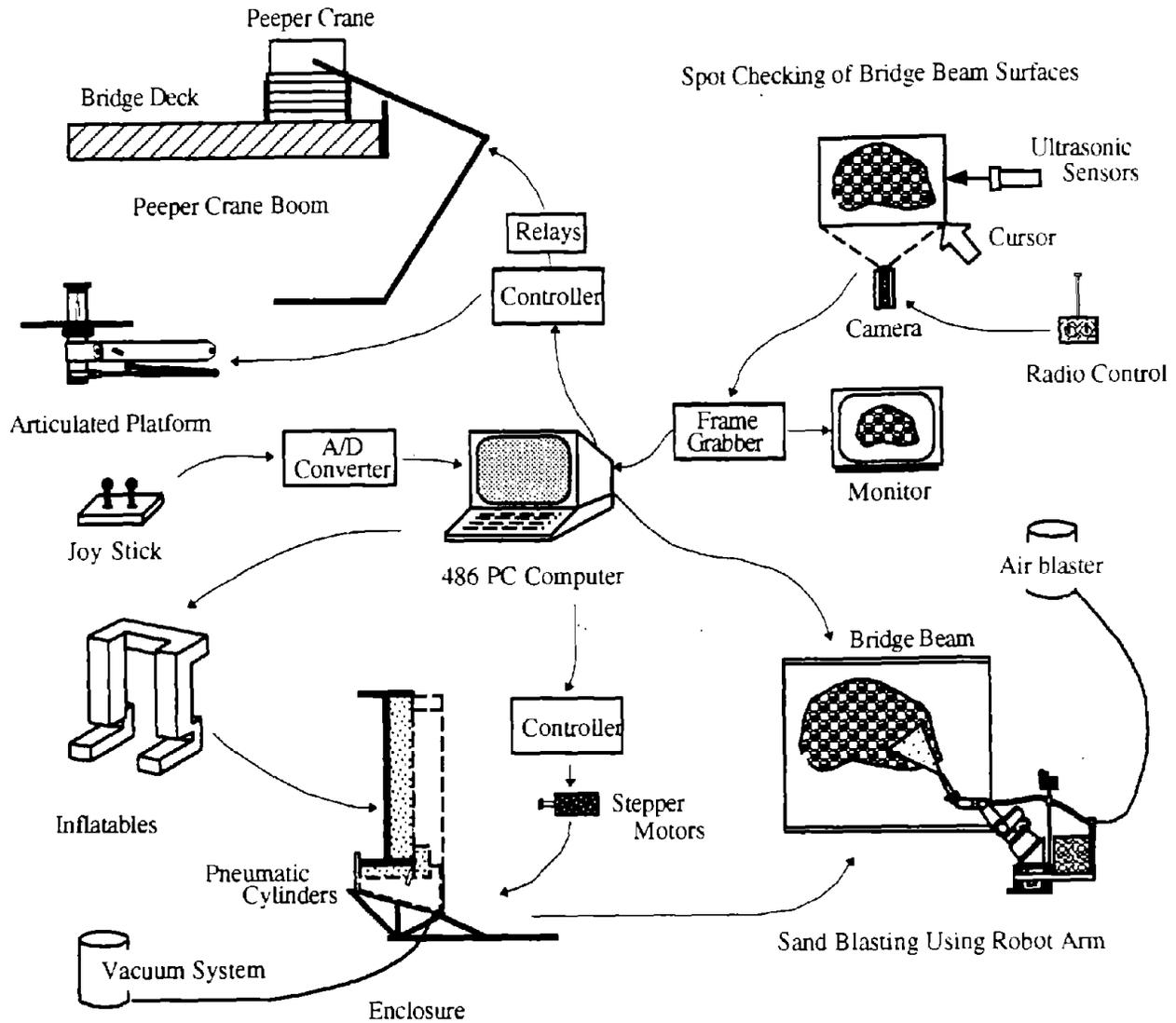

Figure 5. Modularized control system architecture for the RBPR.

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An 80486-based personal computer (PC) is used as the main vehicle to integrate all of the modules and to provide human-machine interface capabilities. The human-machine interface includes several subcomponents such as: 1) two joysticks, 2) video camera with monitor, 3) frame grabber-based computer interface, 4) computer key board, 5) computer graphics with real-time status reports, and 6) radio for the camera. The PC allows not only for easy data and command exchange between the control modules and the human operator but also for the programming of fully autonomous components.

The computer hardware offers a means for interfacing a variety of auxiliary data communication devices. The data communication is based on analog-to-digital (A/D) or digital-to-analog (D/A) conversion boards. On an elementary level, the D/A boards offer programmable solenoid relays that can function as on/off switches for electronic valves. This technology was extensively used for controlling the RBPR system because of its simplicity and effectiveness. Since the Peeper crane uses electronic solenoids to actuate the hydraulic cylinders, it provided a method to integrate the RBPR system with the existing truck.

Electro-hydraulic valves operating several hydraulic cylinders and a hydraulic motor are used for moving the actuated platform. Stepper motors are used for non-binary motion control. Stepper motors interpret digital commands from the computer (e.g. the number of revolutions or position steps), to move the two linear motion tables mounted on the articulated platform. The frame grabber board converts video images into computer data. Printer and communication ports are used as standardized connections that can be easily exploited.

STRATEGIES FOR MOTION CONTROL

Five different motion control strategies were developed to accommodate the task specific constraints and the configuration of the different system components. These include: 1) remotely controlled deployment of the crane boom, 2) telerobotic deployment of the crane boom, 3) autonomous final positioning of the actuated platform, 4) autonomous positioning of the containment box and robot arm, and 5) robotic manipulation of the blast nozzle.

Telerobotic operation is a manual control procedure to position the crane boom using joysticks and a remote camera. The joysticks are connected to a D/A conversion board within the PC computer. The D/A board, in turn, electrically activates the hydraulic valves of the crane boom and the platform actuators. Since the blast cleaning takes place under the bridge deck, the control of the RBPR system largely relies on the live visual images from a video camera and real-time input data from ultrasonic sensors.

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Two separate autonomous operations position the actuated platform and containment enclosure in front of the bridge beam. Sensors are used for avoiding collisions with the existing structures under the bridge deck and for locating the platform at a desired section on the bridge structure. The sensory data are also used to compute the current status of the platform and to maintain its proper alignment relative to the bridge beam and deck. This ensures the containment box will effectively enclose the necessary area on the beam.

The actual paint removal process uses visual data generated by a vision system developed for this project. The vision system hardware consists of a video camera, a closed-circuit TV monitor, a frame grabber, and a radio controller. Operators locate a corroded beam surface through visual inspection while watching the monitor screen. A box is then drawn by the operator around the corroded area displayed on the monitor using the PC mouse interface. A path planning algorithm then generates the robot path using the necessary kinematic equations. Based on the joint angles calculated by the robot path planning algorithm, the robot arm points the venturi nozzle on the blast area and initiates the blasting work.

The robot arm used for this project is an articulated joint robot. The robot arm is mounted at a 45 degree angle to reach all the surface areas of the bridge beam. The robot controller utilizes inverse kinematic solutions for robot path planning. Path planning algorithms are programmed such that the robot arm can complete abrasive blasting of the bridge structure that is within its reach.

6. RAPID PROTOTYPING

OPERATIONAL TESTS AS MILESTONE EVENTS

The development of complex devices such as the RBPR system requires careful planning and execution. Self-contained modules allow for the definition of milestones whereby operational tests must be passed prior to proceeding. In the RBPR system, the subcomponents of the modularized control architecture were defined and operationally tested to acquire the parameters necessary for establishing final designs. The operational testing also was used for demonstrating the potential applications of the prototype RBPR system to bridge paint removal. Figure 6 shows the deployment of the RBPR system for field experimentations.
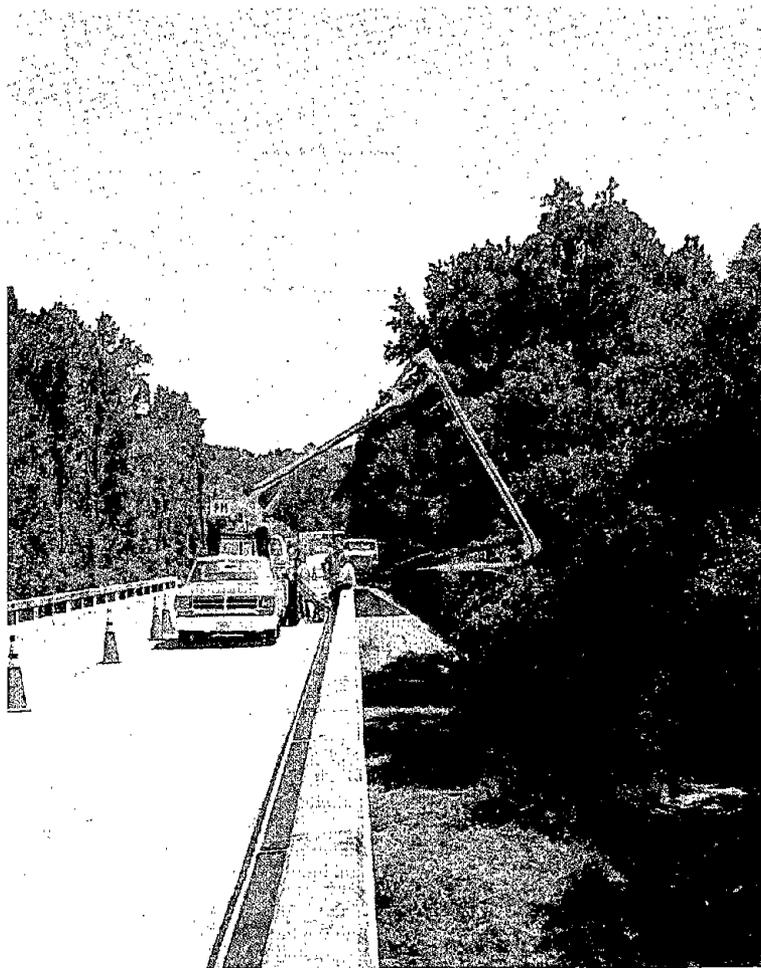

Figure 6. Deployment of the RBPR system for field experiments.

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Several field tests were performed during the development of the RBPR computer-integrated control system. Included in these operational tests was the field demonstration on Aug. 17, 1994 over a 0.91 m (3 ft) steel girder bridge on the Auburn-Knightdale road in Raleigh, North Carolina. The tests included verification of the computer-integrated control of the crane boom and the platform actuator. The results of the field experiment showed that the control system architecture can be effectively integrated into the electronic control system existing in the Peeper crane and can provide the RBPR system with sufficient flexibility in the dynamic working environment under the bridge deck. Figure 7 shows the prototype end-effector system positioned under the bridge deck.
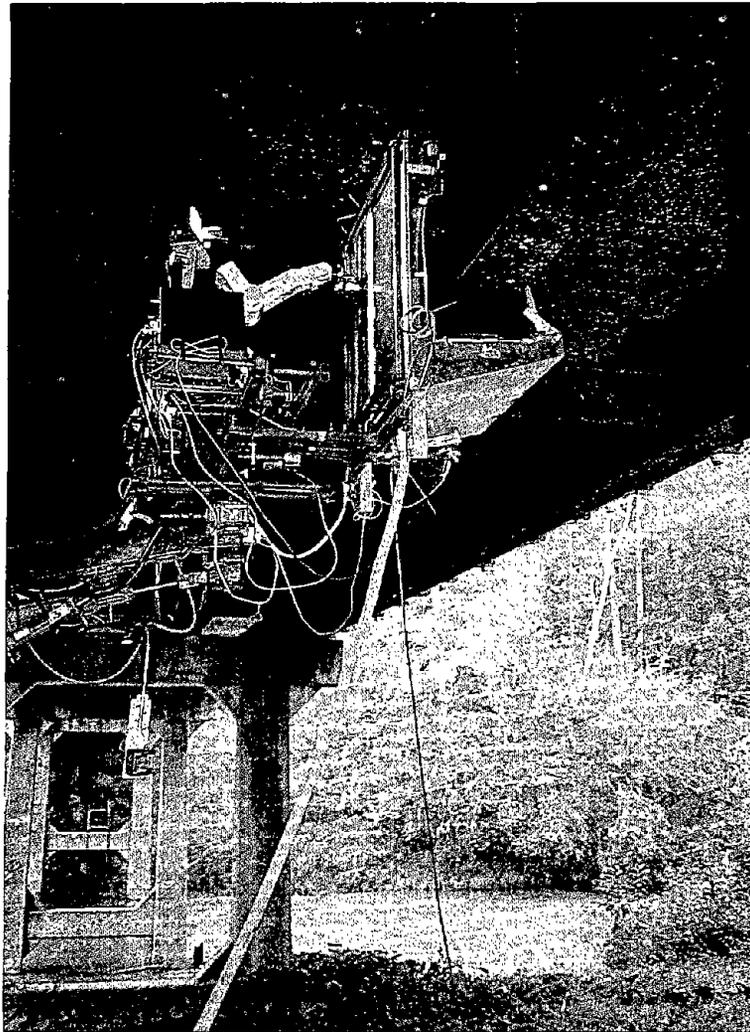

Figure 7. The end-effector in action under the bridge deck.

PERFORMANCE OF SYSTEM COMPONENTS

The following section provides observations of each of the major components during the various field tests.

Peeper Crane Truck

One lane of the bridge was occupied for positioning the crane truck during the field test. When extended under the bridge deck, the crane boom could reach up to approximately 6 m (20 ft) horizontally. The hydraulic system of the crane boom was strong enough to effectively handle the end-effector system of the RBPR which weighs up to 270 kg (600 lb). The hydraulic valves were operated using toggle switches, located in the crane control box, or joy sticks connected to a PC computer.

Actuated Platform

The actuated platform was easy to control and provided high mobility. The four degree of freedom provided sufficient flexibility as required to position the platform against the bridge beam. The end effector system was connected to the crane boom at the testing site. As a result, the setup caused a time delay before the actual operation was executed. For practical application, easy installation or transportation methods were deemed necessary. Thus, a small-size hand crane was mounted on the crane to aid the setup operation. It allowed a single operator to install the platform and reduced the time required for setup.

Robotic Blasting System

Robot Arm: The articulated joint robot arm configuration was flexible and very effective in performing various blast tasks as required for the paint removal from the bridge beam. However, the micro robot arm could only handle objects weighing up to 5.5 kg (12 lb) and was not sufficient to handle the weight of the gripper, the nozzle and the blast hose that were used for the RBPR system. The limited loading capacity of the robot arm required the robot path planning process to be monitored very closely. When the robot arm failed due to the high loading pressure, the arm had to re-orient itself for positioning before starting again. This constraint made the robot arm manipulation very difficult.

Linear Sliding Table: Using two linear sliding tables enabled the robot arm and the enclosure chamber to move independent to each other. This provided flexibility that allows for inspecting the beam surface condition and blasting the corroded paint at the same time. The stepper motors used for the two sliding tables were highly accurate for keeping track of the position of the robot arm and the enclosure.

Abrasive Blasting: Back pressure was measured to be less than 4.5 kg (10 lb) with different blasting pressures ranging from 4.2 kg/cm^2 (60 lbf/in^2) to 8.4 kg/cm^2 (120 lbf/in^2). The abrasive blasting method used for the RBPR system eased the control requirement. The abrasive blast appears to be a very efficient approach that can speed up the blast process for different blast surfaces such as diaphragms and bearings.

The 8 mm (5/16 in) venturi nozzle creates a 15 mm (6 in) wide cleaned surface at a distance of approximately 30 cm (1 ft). The blasting method cleaned the blast surface clean enough to meet the requirement of the SSPC specification (SSPC-VIS 1-89).

Spot cleaning was intended to preserve the existing good paint surface and remove only the corroded paint. The vision-based control method demonstrated that the blast area can be cleaned with ± 2.5 cm (1 in) deviation. The error occurred largely due to the changes in the physical dimensions, and was considered to be acceptable because of the flexibility of the abrasive blast. The flexibility of the sand blasting technique was able to compensate for inaccuracies in the path planning for the automated paint removal.

Containment Box

Inflatable Enclosure: The containment box was shown to be very effective in creating a confined area to capture paint debris, blast media and dust. Since the enclosure was built specifically for 0.91 m (3 ft) bridge beams, the box needed to be designed such that it can accommodate different sized bridge beams. The inflatable mechanism provided adaptability to changing structural profiles within a certain range. The mechanism also served as a damper against traffic shocks and vibration occurring on bridge beams. However, the plastic tube inside the rubber enclosure was not strong enough to withstand accidental increase of air pressure.

Brush Opening: Brush skirted openings allow for the projection of the blast nozzle mounted on the robot arm while maintaining a confined area for debris collection. The narrow distance of the opening, however, made it difficult for the robot arm to move up and down within the opening. Since the brush opening was activated by the horizontal force of the robot arm, it was difficult to locate the accurate position of the robot arm. Also, imprecision in the containment box positioning system made it difficult for the robot arm to find the opening. An opening with a large diameter is required for the ease of the robot arm movement.

Vacuuming: Dust control is a very important aspect that can be used as a measure of the effectiveness of the robotic bridge paint removal. The rubber material used as the flexible enclosure mechanism effectively generated a confined area and contained paint and blast debris.

The vacuum system used one venturi nozzle and was powerful enough to remove the debris quickly from the enclosure. A vacuum system with two venturi nozzles can increase the capacity significantly. However, the configuration of the enclosure mechanism caused some part of the debris to be stuck in the corner. Since the brush opening created an air inlet, no negative pressure inside the enclosure was noticed.

Vision System/ Sensors

Camera with a Zoom: A camera was used to provide visual feedback in the manual control of the crane boom under the bridge deck. The limited camera view, however, made it difficult to rely solely on the camera for positioning the end effector. The video camera was also used for visual inspection of surface conditions.

Since the camera was installed on the linear sliding table that is used for the robot arm, the operator could move around the camera on the actuated platform to inspect the surface condition of the bridge beam before and after blasting. A clear view was provided of the blasting work through the transparent fabric of the enclosure mechanism. Also, the radio-controlled zoom of the camera lens allowed for zoom-in and zoom-out for close-up viewing of the surface conditions. Using the camera and the monitor, the surface condition can be taped to document the results of the blast cleaning operation.

Panning Device: The panning device was made of a proportional drive unit. A radio control device was used for remote control. The panning device provided a capability to show the various parts of the working area under the bridge deck.

Sensors: Ultrasonic sensors were used to effectively perform collision avoidance and positioning. The sensors provided accurate distance measurement of the objects under the bridge deck. Such numerical position data, together with the visual feedback from camera, helped manual positioning of the end effector system.

PERFORMANCE OF CONTROL MODULES

The following section provides observations of the control modules during the various field tests

Monitoring

Visual Aid: The vision system showed the actual conditions under the bridge deck on a monitor. However, the limited viewing area made it difficult to rely upon a camera as the only monitoring method.

Sensory Data Input: The sensors provided distance measurements that indicated the horizontal, vertical, and parallel positions of the crane boom and the articulated platform. Data were used to perceive the clearances of the end effector from any objects under the bridge deck. Human operators could constantly watch the distances on the computer screen and make decisions in the manual telerobotic operation using a computer key board or joysticks.

Interpretation

Image Processing Analysis: The vision system served as a tool for image processing and analysis. This approach provided a unique capability to overcome the problems often encountered in telerobotic operation. Through a graphic interface, the operator could locate the corroded paint area and automatically move the robot arm to execute the blast work.

Pattern recognition: The distance data input from the ultrasonic sensors mounted on the enclosure indicate the position status in the working space. The pattern of the distance data in a certain stage can be associated with the control strategy for the Peeper crane. Such pattern recognition algorithms can provide a capability to evaluate the feedback data and to define the current status of the RBPR system.

Automation/Actuation

Automated Path Planning: The vision control system provided a capability of remote control for executing spot cleaning. The vision control was used to locate the corroded area and to generate the robot arm path for abrasive blasting. The combined motion of the robot arm and the linear sliding table effectively covered the blast area required for the spot cleaning.

Remote Control

***Computer Control*:** Computer control was used as a central control mechanism. The computer integration allowed for controlling the joysticks, the relay switches, the stepper motors and the robot arm. Computerized control demonstrated an opportunity for full automation of the RBPR system.

***Joystick Control*:** Joysticks were used for deploying the end effector system under the bridge deck. Unlike the toggle switches on the Peeper crane, the joysticks provided an interface with the computer. This suggests the potential for fully computerized control as well as autonomous machine control. Using the joystick, the control mode could be changed from the end effector control to the crane boom control, and vice versa.

***Radio Control*:** Radio control was used for zoom features on the camera lens and for panning the camera base. Radio control was useful as a way of removing wires as much as possible. Also, the direct connection between the control device and the mechanism under control could help simplify the system configuration and functional reliability.

Human Operator Supervisory

***End Effector Positioning*:** For the field test of the RBPR system, manual operation was used to evaluate the reliability of the control system. Although a computer algorithm can provide an autonomous capability for maneuvering the crane, man-machine interfaces provide more reliable and efficient control for the paint removal process.

***Blasting/ Vacuum Procedure*:** For the field test, the blast and vacuum system was activated by manual control. By utilizing electronic switches for blasting and vacuuming, the operation can be easily automated.

7. SUMMARY

Many steel girder bridges were coated with lead-based paint until the 1970's when toxic lead became a national health issue. Recently, OSHA regulations have become extremely restrictive in order to protect workers' and the public's health as well as the natural environment. The RBPR project was initiated to provide a safe working environment during the bridge paint removal operation. The requirement of dust containment coupled with the unique shape of the bridge beam caused special problems in developing the RBPR system. The constraints, in turn, offered challenges to come up with innovative solutions for the design, development and fabrication of a novel solution. The robotic paradigm, along with vision-based computer control, provided an efficient mechanism for spot cleaning of corroded paint. Several field tests during the developmental process provided opportunities to evaluate design concepts and to demonstrate a working prototype of the RBPR system. The close relationship between CARL and NC DOT was instrumental and made it possible to achieve the project goal within the given time and budget while ensuring the practicality of the result. The accumulated technology and experiences will be invaluable in an effort to expand the prototype system into a complete bridge maintenance system that includes painting, washing, and inspection.

8. RECOMMENDATIONS

The RBPR system was designed as a prototype for automated bridge paint removal. In order to improve the performance of the RBPR system, future work should focus on:

1) Increase of flexibility of the enclosure for different bridge shapes.
2) Increase of loading capacity of the robot arm.
3) Reduction of setup time.
4) Development of a control system for automatically deploying the end effector.
5) Preparation of a backup control system.

The concept of the RBPR system design could be easily modified to include various tasks that are related to bridge paint maintenance. A cost-effective approach will result from an integrated maintenance system that includes various technologies in the areas of inspection, painting, washing, and paint removal. The fundamental concept and technologies developed for the RBPR project can be used as a basis on which the integrated system could be built. The following new capabilities can be added for future study:

a) Contained spray-washing of bridge girders (to remove loose paint, dirt, salt.)
b) Robotic paint application after paint-removal.
c) Paint removal from the diaphragm.
d) Paint removal from the bridge bearings.

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