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Robotic Bridge Maintenance System

by

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and
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DEPARTMENT OF CIVIL ENGINEERING

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Final Report

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16 Abstract

This report describes the development of a Robotic Bridge Maintenance System (RBMS) jointly developed by the North Carolina Department of Transportation (NCDOT) and the Construction Automation and Robotics Laboratory (CARL) at North Carolina State University (NCSU). The system allows an operator to be removed from the dangerous environment under the bridge deck and allows him/her to teleoperate the entire bridge maintenance procedure.

One of the major advantages that this system has over others is that it has been designed as a relatively simple modification to existing equipment. The tracks and robot mount directly to the under bridge crane with four bolts and four quick connect lines. This also has the advantage of making the system easy to transport. Another advantage is the use of a robot to perform the tedious bridge maintenance procedure. By using a robot and a universal gripper, virtually any type of blasting method can be used. Additionally, the robot can be used for other types of applications in which a tool needs to be manipulated, and it is desirable to place the worker at a safe distance.

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Robotic Bridge Maintenance System

by

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in cooperation with
North Carolina Department of Transportation

CENTER FOR TRANSPORTATION ENGINEERING STUDIES

Department of Civil Engineering
North Carolina State University

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ABSTRACT

This report describes the development of a Robotic Bridge Maintenance System (RBMS) jointly developed by the North Carolina Department of Transportation (NCDOT) and the Construction Automation and Robotics Laboratory (CARL) at North Carolina State University (NCSU). The system allows an operator to be removed from the dangerous environment under the bridge deck and allows him/her to teleoperate the entire bridge maintenance procedure.

One of the major advantages that this system has over others is that it has been designed as a relatively simple modification to existing equipment. The tracks and robot mount directly to the under bridge crane with four bolts and four quick connect lines. This also has the advantage of making the system easy to transport. Another advantage is the use of a robot to perform the tedious bridge maintenance procedure. By using a robot and a universal gripper, virtually any type of blasting method can be used. Additionally, the robot can be used for other types of applications in which a tool needs to be manipulated, and it is desirable to place the worker at a safe distance.

1. INTRODUCTION

Robotic systems for construction applications have advanced dramatically over the past few years. Automated systems were initially developed to reduce labor requirements, shorten construction time, reduce costs, and improve quality. Currently, benefits such as moving workers out of the dangerous work areas and conformance to agency standards such as those set by the Environmental Protection Agency (EPA), the Toxic Substance Control Act (TSCA), and the Occupational Safety and Health Administration (OSHA) have improved the workers' environment and improved worker morale.

Steel bridge painting operations are dangerous and hazardous to human health. A typical maintenance operation involves sandblasting the steel surface to remove old paint and rust, and then painting to protect the surface from the environment. This work is performed manually using a scaffold or similar device to access the work areas that must be completely encased due to the lead content in the paint. Heavy equipment and protective clothing are also required. The protective clothing that workers wear is very hot, especially in warmer climates. This leads to rapid fatigue and workers having to break at regular intervals to regain their strength.

Workers are exposed to not only the harmful paint components such as lead, but also to the risk of falling. According to the National Safety Council, seventy percent of all serious injuries to coating workers are caused by falls. Strenuous working conditions and worker fatigue can contribute to an inconsistent quality of the applied painting. This hazardous painting procedure is therefore well suited for automation techniques.

Development is justified by the potential improvements in safety, quality, and productivity. With the robotic bridge maintenance system, human operators will be removed from the dangerous work environment location under the bridge deck to a safe place on top of the deck. There they can tele-operate (remotely control) the robotic system without risking their health or their lives. The quality of painting is also improved because the robotic system does not suffer from exhaustion or fatigue as a human operator does. A consistent, high quality painted surface is then obtained. By protecting the worker from hazardous environments, productivity can be greatly increased.

Other systems that have been developed include the Aerial Platform developed by the California Department of Transportation. [Woo, 1995] This system only performs the inspection of the bridge. Another system is the Robotic Trunk System developed by the FHWA Research and Development Division. [Wu, et.al., 1996]

With help from the Federal Highway Administration (FHWA) and the North Carolina Department of Transportation (NCDOT), the Construction Automation and Robotics Laboratory (CARL) at North Carolina State University (NCSU) has successfully developed a prototype Robotic Bridge Maintenance System (RBMS). The system consists of a modified under bridge crane with a robotic arm and containment system attached to the end. The system has the capability to perform video inspection, contained sandblasting, painting, and spray washing of steel bridge beams and bridge bearings. From an economic standpoint, it is practical to have one robotic system to do all of these jobs. The focus of this report will be to present an overview of the developed system and highlight its advantages and potential.

2. RESEARCH OBJECTIVES

The basic objective of the research was to expand the capabilities of the Robotic Paint Removal System (RPRS) developed by Bernold and Moon, [1995]. Figure 1 shows the system being tested on an actual bridge in August of 1994. It was designed to enable the evaluation of several paint removal technologies on bridge structures for their applicability to robotic control. The fundamental concept of that system, seen in Figure 2, was based on the use of a traditional under bridge crane as a vehicle to position a sophisticated end-effector mounted at the end of the boom. Thus, only an attachment would have to be built when the prototype system was brought to commercialization. Through experimental tests in the field the level of automated control which could be achieved for each technology was investigated. The flexibility of the prototype, however, allowed for modification of the base system. The scope of this research was to add and field-test the following new capabilities:

a) Remote visual inspection of the bridge structure
b) Contained spray-washing of bridge beams (to remove loose paint, dirt, salt, etc.)
c) Contained paint removal from bridge beams and trusses by sandblasting
d) Contained paint removal from bridge bearings
e) Robotic paint application after paint removal

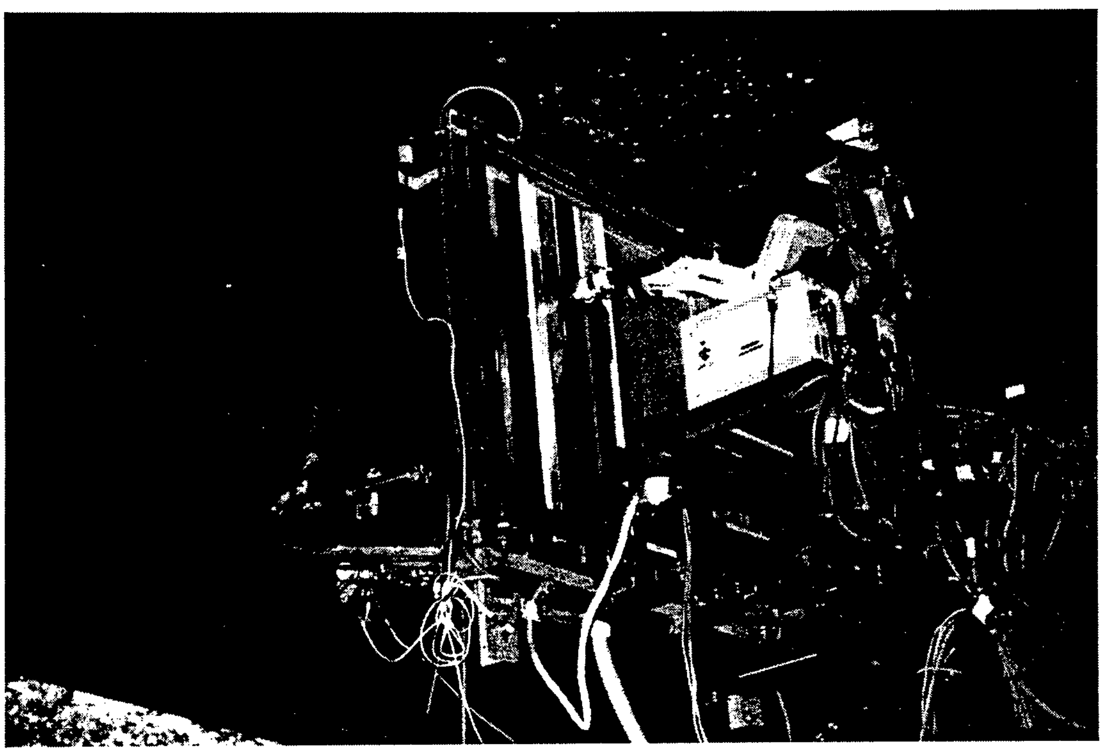


Figure 1: Robotic Paint Removal System (1994)

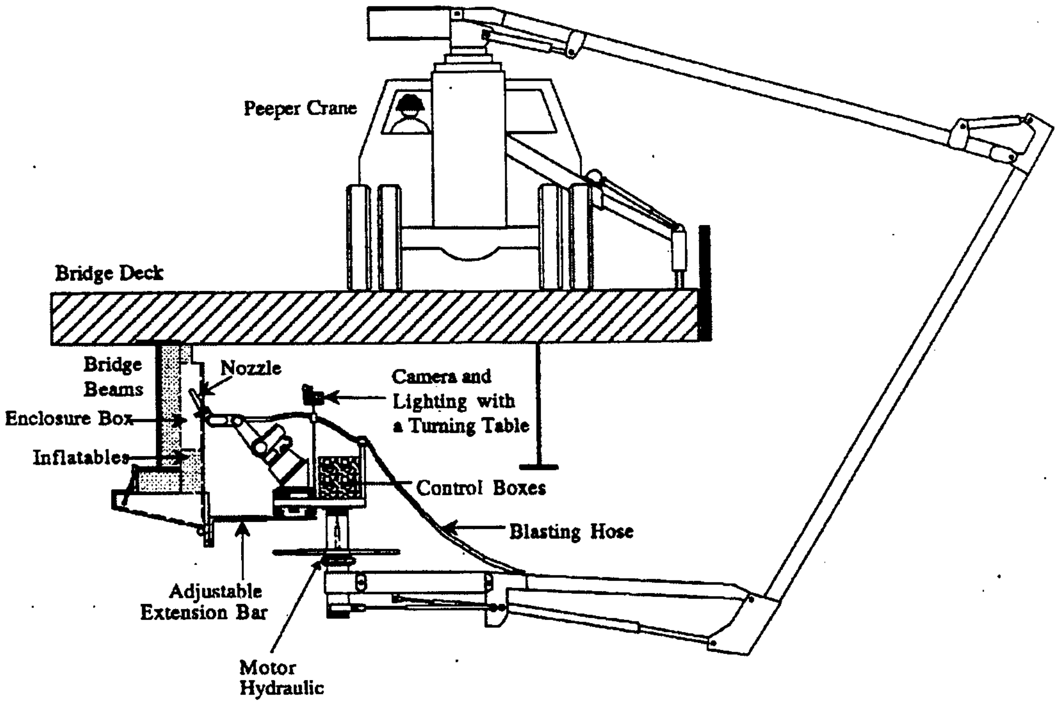


Figure 2: Conceptual Drawing of the Robotic Paint Removal System

Each task of the project followed these generic steps:

1) Definition of new capabilities in cooperation with representatives from NCDOT. Establishment of critical performance criteria for the selected operations.
2) Assessment of present procedures (e.g. cost).
3) Modifications and development of a prototype system.
4) Field testing of the prototype systems. Assessment of performances according to the selected criteria.

3. FINAL VERSION OF PROTOTYPE HARDWARE

The RBMS has four main capabilities: remote inspection, spray washing, paint removal, and painting. The basic goals of the system were to eliminate the need for a human to be involved directly in the removal process and to contain the lead-based paint. Additionally, the system was to be developed as an attachment to an existing under bridge crane. This reduced the cost of the entire system.

The RBMS was tested at the Bridge Maintenance Facility at the NCDOT depot in Raleigh, NC. (see Figure 3) The only modifications which were made to the truck were to route the electrical and hydraulic cables along the boom and the installation of encoders on each of the joints of the boom as shown in Figure 4. Each encoder provides angular position feedback for each joint of the boom so that the boom can be tele-operated.

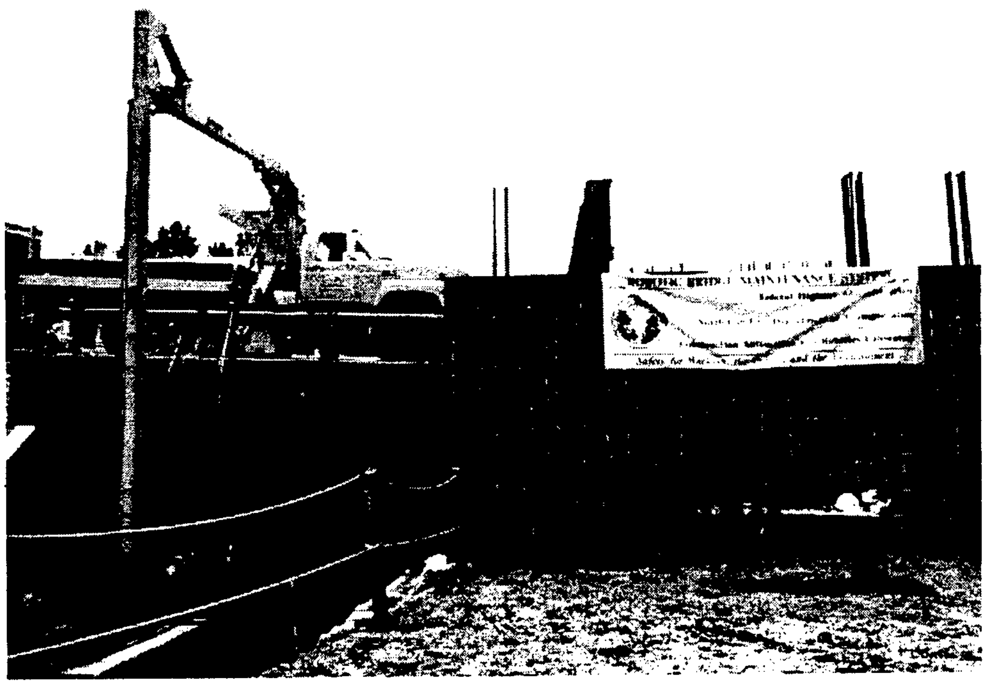


Figure 3: Testing Facility at NCDOT

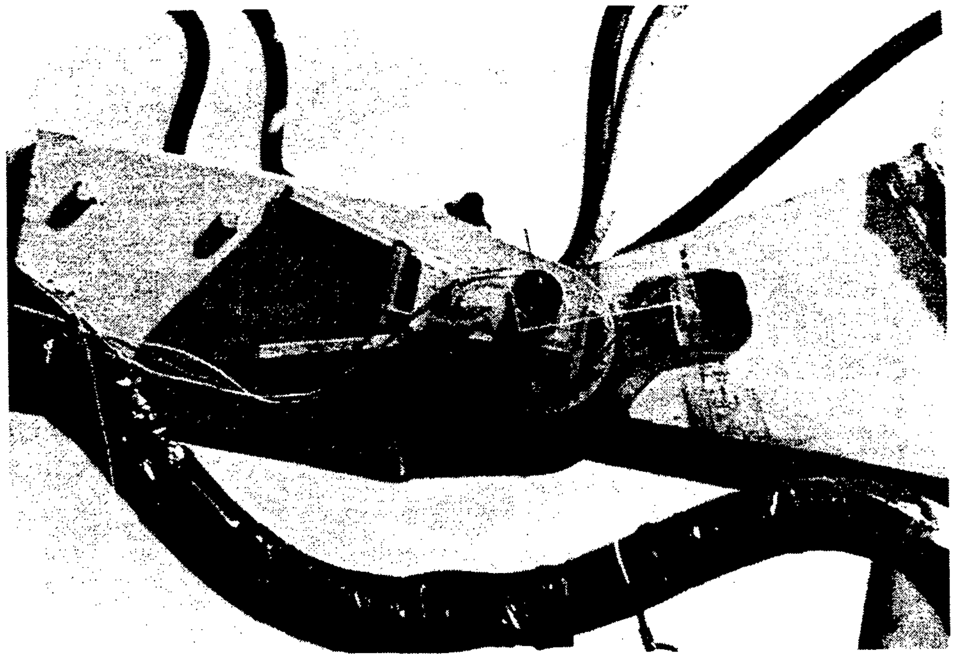


Figure 4: Encoder Mounted on a Joint of the Crane Boom

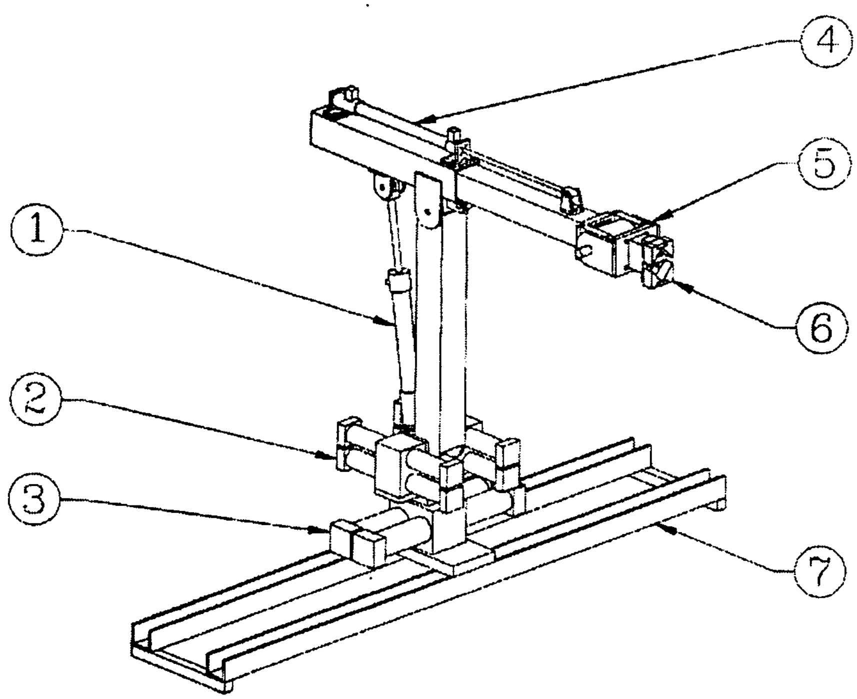
The bucket originally mounted on the end of the crane boom was removed and replaced with an articulated platform for the robotic system. Figures 5 (a) and (b) show the platform attached to the crane boom. The platform is hydraulically actuated with proportional valves and four cylinders and one rotary actuator. Each of these actuators are remotely controlled via a computer with position feedback coming from the sonar sensors mounted on the track system and the crane boom. With this information it is possible to position/orient the robotic system within the robot arm's workspace. This positioning is accomplished with the Overlay Crane Control which is a global control scheme. (This control method is described in detail in the next chapter.)

(a) Overall View **(b) Close-Up of Articulated Platform**

Figure 5: Articulated Platform for the Robotic System

A track system is mounted on the articulated platform. The robot mounts to a trolley on top of the tracks which provides lateral motion to the robot for spray-washing, sandblasting, and painting procedures. A second trolley is mounted underneath the tracks to which the containment system is attached. Each trolley is moved independently with a hydraulic rotary actuator and a chain drive. Each actuator has a potentiometer mounted on the shaft for feedback to the computer of the position of the trolley along the tracks. When the robot and the containment system are required to move simultaneously, the coordination is provided through software.

The commercial robot which was used for the RPRS was replaced for the RBMS since it was found to not be strong enough for the application. A new hydraulically actuated robot was designed and built at the Precision Machine Shop at North Carolina State University. The robot, shown in Figure 6, has five degrees of freedom and was designed in order to have the ability to reach into tight areas. It is a hydraulically actuated five degree-of-freedom robot mounted on a track system attached to the end of an under bridge crane. The five degrees of freedom are provided by cylinders 1-5 in shown in Figure 6. An additional sixth degree of freedom is provided by the tracks.



1. **Elbow Pivot Cylinder**
2. **Shoulder Rotation Actuator**
3. **Shoulder Roll Actuator**
4. **Arm Telescopic Cylinder**
5. **Wrist Pitch Actuator**
6. **Pneumatic Gripper**
7. **Track System**

Figure 6: CAD Drawing of the New Robot

The system has been upgraded to perform other tasks. The original Mitsubishi robot that was used has been changed. The new robot was designed and fabricated at NCSU.

The gripper shown in Figure 6 was changed in the final prototype. This gripper was not capable of holding the payload which was required to hold the different tools. A new pneumatic gripper was used. (see Figure 7) This gripper has three "fingers" which extend to hold the universal tool mount. The tool mount is a disk with a unique attachment for each tool. In Figure 7, the sandblast nozzle is attached to the robot. The universality of the disk attachment is that each tool mounts to the robot in an identical manner which makes the tool change process straightforward.

Figure 7: Close-Up of the Universal Gripper

Multiple tools can be used with the RBMS so that all of the bridge maintenance process can be completed without having to redeploy the robot. For visual inspection, a CCD camera is mounted to a bracket on the robot arm as shown in Figure 5(a). The other tools used - a spray washing nozzle, sandblasting nozzle, needle gun, and paint nozzle - are mounted with the universal tool mount. (see Figure 8)

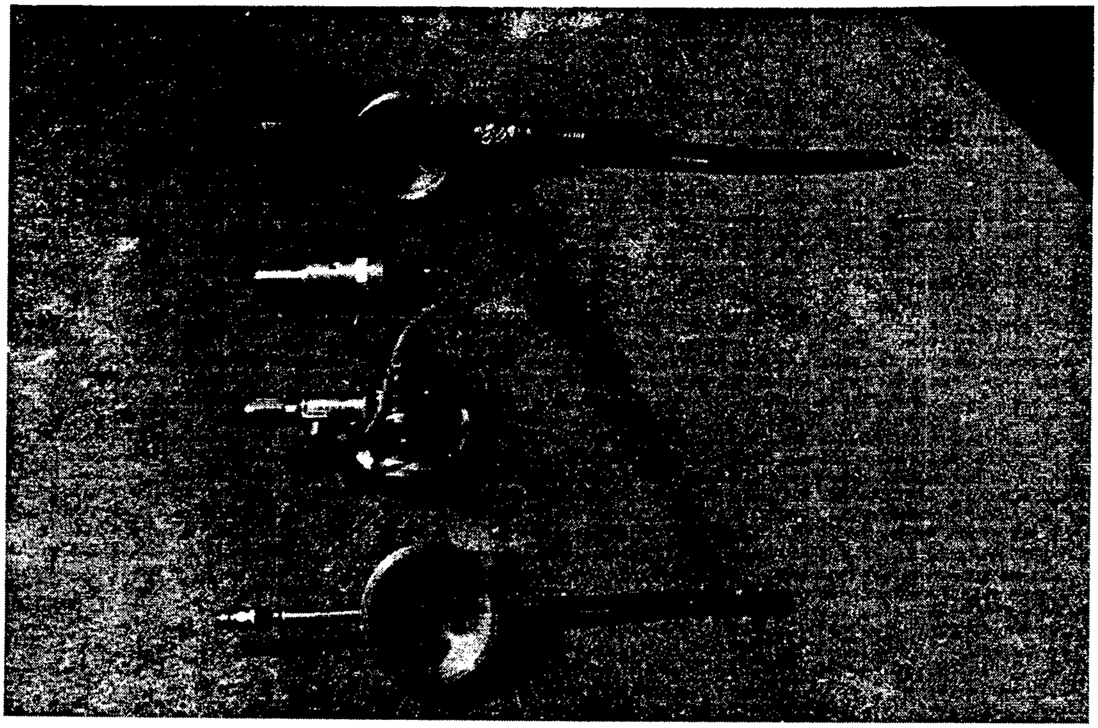


Figure 8: Maintenance Tools
(Top to Bottom:Needle Gun, Sandblast Nozzle, Spray Paint Gun, Pressure Washer)

The final modification of the final prototype was to redesign the containment system. The old system, shown in Figure 1 used rubber inflatables to create a seal against the bridge beam. The new containment system uses two smaller boxes which makes for a much more flexible and adaptable system. (The containment system is described in detail in Section 5.)

The procedure to implement the RBMS begins with the deployment of the crane. If a CAD drawing of the bridge is available, the crane can be deployed autonomously via an overlay algorithm and information from the encoders mounted to each of the joints on the crane boom. Alternatively, if a CAD drawing of the bridge is not available an operator can tele-operate the crane by using the vision system that is part of the RBMS. The vision system consists of two cameras: one mounted on the arm of the robot as shown in Figure 5(a) and a second camera placed at a distance on the bridge perpendicular to the plane created by the crane.

Once the crane is deployed underneath the bridge, the sonars mounted on the crane boom, the robot, and the containment system, are used to position the robot at an acceptable distance from the bridge beam. (The distance is defined by the work-space of the robot.) An articulated platform onto which the robot's track system is mounted is used for final positioning so that the containment box can be placed flush against the web of the bridge beam.

With the robot positioned under the bridge, the maintenance procedure can continue. The first step is the inspection process. Using the camera mounted on the robot's arm the operator can inspect the beam for spots that need to be repaired or cleaned. The robot can now be controlled to spray wash, sandblast, and/or paint the beam.

4. SYSTEM COMPUTER CONTROL

The control of the system can be divided into two parts: a gross control which positions the crane, and a fine control which controls the end-effector. The two are separated because it is impossible to obtain precise positioning due the nature of the crane. The crane control positions the robotic system into its workspace and then the robot can perform the bridge maintenance. It is possible to control the crane and the robot individually or simultaneously.

Crane Control

A graphic-based path planner is built in a graphic environment of CAD for efficient telerobotic operation of construction manipulators (Figure 9). The CAD integration provides a user-interface for determining the trajectory. The trajectory is drawn in a coordinate system developed for the working environment. The geometric configuration of the trajectory is depicted using a Bezier curve. The path from the starting position to the goal position can be divided into a number of via points. Using inverse kinematics, the planner calculates joint angles that are necessary to automatically move the manipulator to the via point. The capability of collision avoidance is added to provide a real-time manipulator control. Key aspects of the main architecture are described in detail as the following:

Structure of Coordinate Frame: A coordinate system is structured in order to keep track of the manipulator position in relation to the world coordinate of the bridge deck. The overall coordinate system is made up of several local coordinate systems that include bridge, crane, crane boom base, four crane boom joints, two cameras, and target coordinates. The bridge coordinate serves as a world coordinate and is used as a reference point by which the position and orientation of the end-effector can be indicated. Any point within the work space around the bridge structure can be indicated for systematic representation of the manipulation position.

Bezier Curves: The manipulator path is represented as a space curve traced by the manipulator from a starting position to a desired destination. The mathematical function may be as simple as a straight line or so complicated that they require a high-order polynomial description. The Bezier function is used to describe the manipulator path for off-line path planning. The mathematical description of the curves provides trajectory data required for the telerobotic operation of construction manipulators.

Inverse kinematics/ forward kinematics: The retrofitted under bridge crane has spatial joints with four degrees of freedom. Given the via points, an inverse kinematic algorithm is invoked to calculate the joint angles of the crane boom sections and to store the results in a trajectory table. Using the trajectory table, the deployment of the manipulator is graphically simulated in a CAD environment.

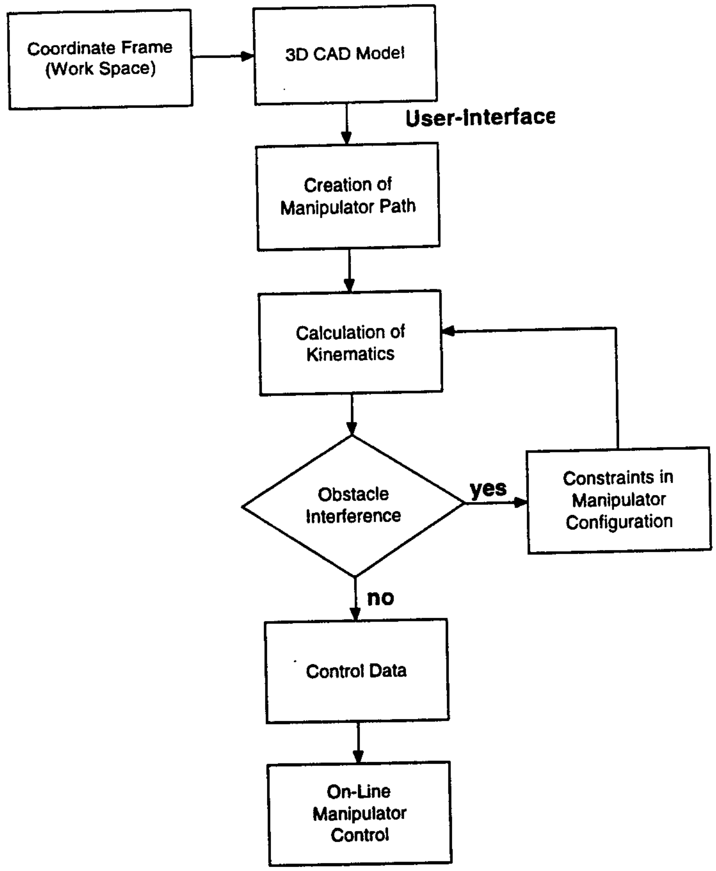


Figure 9: Graphic-Based Off-Line Path Planning

Collision avoidance: In order to avoid collision with obstacles on the manipulator path, constraints should be given for the calculation of inverse kinematics. The task is to solve the kinematics problem such that the crane boom can avoid these objects. Ultrasonic sensors with wide beam angles are used for detecting obstacles. They are mounted on the crane boom. Whenever the boom approaches an obstacle, the sensors indicate the distance, and display warning signs. The distance is then used for calculating the inverse kinematics in order to create the configuration of the crane boom.

This architecture provides a means to graphically simulate the motion of the crane boom on the planned path. Figure 10 shows a CAD model of the crane boom being animated following the generated path. During the simulation, human operators inspect the CAD model at various viewing angles using a dynamic view function, and indicate the start and goal positions. Through visual inspection, they can understand the required configurations of the crane boom, as well as identify the obstacle interference that may be encountered during field operations. During the simulation, operators can gain familiarity with the control requirements, and develop a control strategy. The procedure can be repeated until a feasible trajectory is selected given a particular site condition. The trajectory is then used for automatically deploying manipulator booms under the bridge deck.

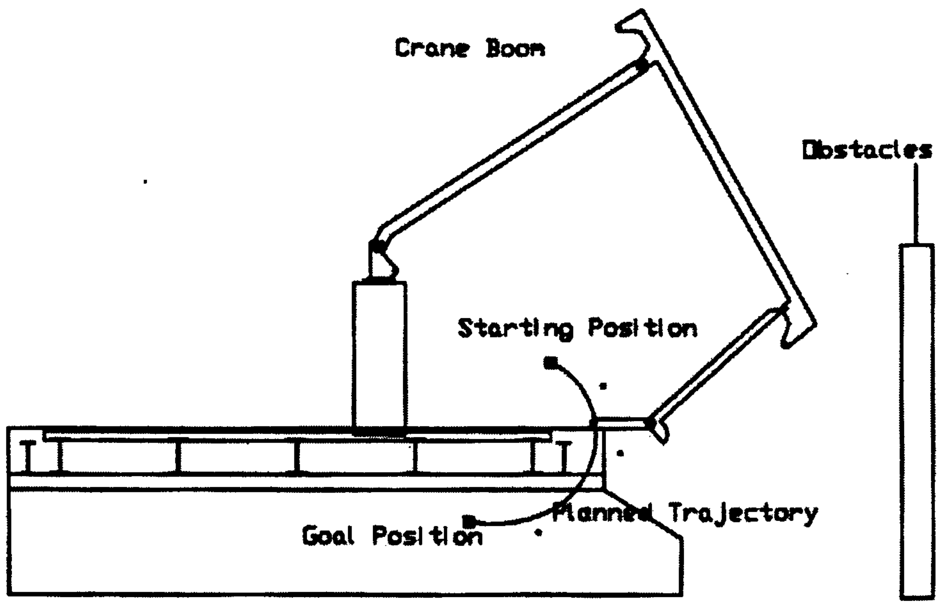


Figure 10: CAD Simulation of Manipulator Motion on the Planned Path

The control architecture of off-line path planning was tested utilizing a large-scale construction manipulator. The under bridge crane and the testing facility at NCDOT were used for this experiment. A virtual control model is designed to support the efficient human-machine interface during on-line manipulator control. The model is built such that the data from the off-line path planning can be directly used for advancing the crane boom under the bridge deck. The control model takes advantage of a 3D CAD model that is superimposed onto live camera images. The model provides a means for the operator to interact with the machine controller on a real-time basis. The procedure of implementing the control method was performed in the following manner 1) selection of via points; 2) creation of a trajectory; 3) collision avoidance with obstacles; 4) graphic simulation of actual deployment; 5) evaluation of the results; 6) selection of a feasible path; and 7) implementation of the accepted path for on-line manipulator control.

During the field experiment (Figure 3), graphic overlay of the CAD model onto live camera images was used to indicate the next via point to which the manipulator should move. Due to the inaccuracy of actual movement the trajectory was constantly updated in order to adjust the originally planned path. In the control loop, the operator played a supervisory role that presides over the telerobotic operation. While looking at a TV monitor, the operator just hits a computer key to advance the crane boom from one via point to next via point.

The typical task completion time for deploying the crane boom ranged between 3 and 4 minutes. The duration approximately matches conventional joy stick control for the under bridge crane control with a full line of sight.

To begin the bridge maintenance process the robot is deployed under the bridge deck via the graphic overlay method. Due to the highly unstructured and constantly changing nature of the bridge environment, it is desirable to use the tele-operated mode of control. The robot is now positioned in its workspace and the maintenance procedure can begin by controlling the robot. [Moon and Bernold, 1997]

End-Effector Control

Figure 11 depicts a flowchart of the subroutine written to control the platform system mounted on the end of the crane boom during the deployment. During deployment the containment box is positioned flush against the web of the bridge I-beam with the tracks parallel to the beam underneath the bridge deck. Visual live images are taken from a camera mounted on the robotic arm to aid the performance. The operators also receive assistance from sensory data which are collected from ultrasonic distance sensors mounted on the crane, the robotic arm and the containment system.

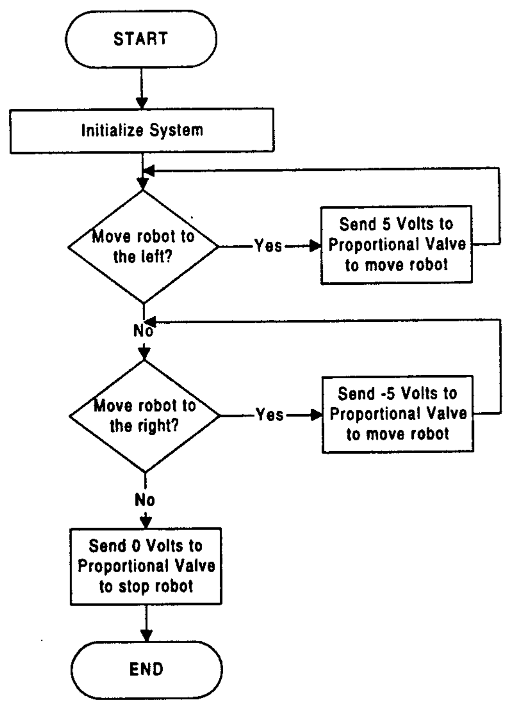


Figure 11: Platform System Control Flow Chart

Figure 12 presents the flow chart of the control procedure of the track sliding motion of the robotic arm. The motion of the joints is accomplished by hydraulic cylinders that are controlled by proportional valves. Oildyne's EMC 5030 signal tracking controllers are used to provide closed-loop motion control.

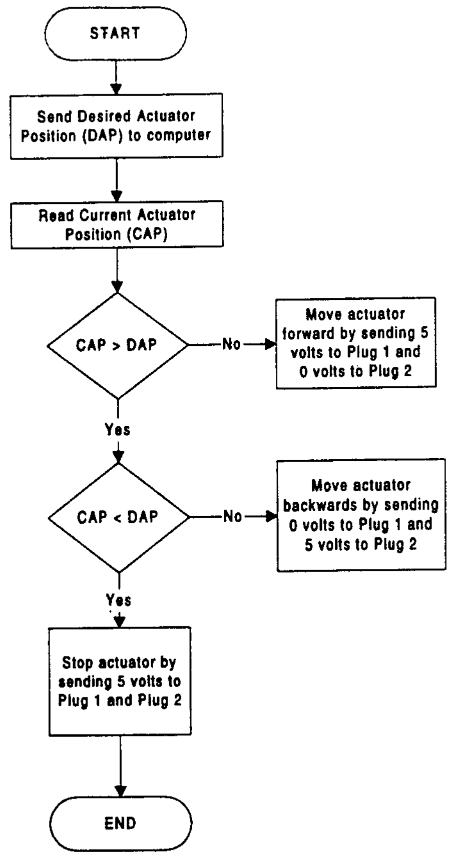


Figure 12: Track Motion Control Diagram

Figure 13 depicts the basic control architecture for the base, shoulder, elbow and wrist.

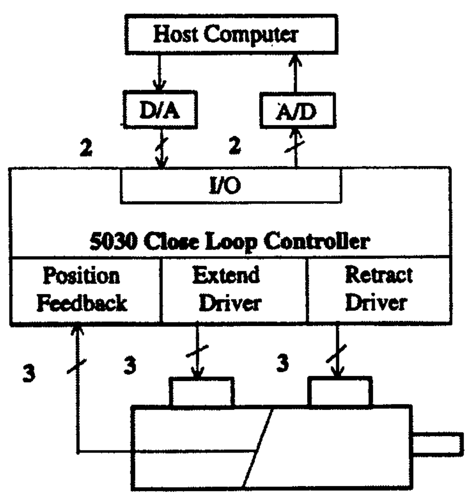


Figure 13: Robot Control Architecture

In the diagram, the A/D and D/A converters are the Opto 22's analog module mounting racks with PAMUX B6 Brain Boards and analog input/output modules (AD12/DA12). The PAMUX B6 Brain Boards is an addressable analog multiplexer for controlling up to 16 channels of inputs and/or outputs in distributed I/O applications. It is connected via a 50 conductor flat ribbon cable to an IBM PC with an inserted AC28 board, which is a high speed IBM PC/XT/AT to PAMUX bus adapter card. The main hardware integration is shown in Figure 14.

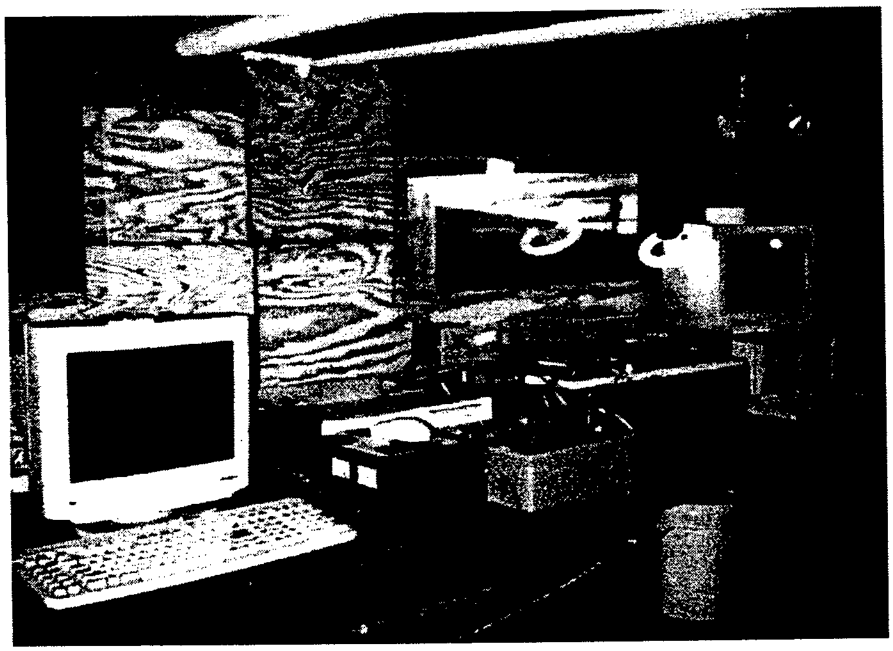


Figure 14: RBMS Control Hardware

Since the toxic debris needs to be contained, the containment system must be locked with the robotic arm in the sandblasting procedure. The relative position between the containment system and the robotic arm along the direction of the table was measured beforehand to make sure that the sandblast nozzle could be centered in the containment box. Once the *locking* command is input to the host computer, the robotic arm and the containment system travels to the docking position. Then, the electro-pneumatic series valve controlled air cylinder extends into the socket on the containment system to simultaneously lock the two components mechanically. The goal of the robotic arm motion is to position the sandblast nozzle into the containment box and keep it -45° relative to the ground.

There are two methods to achieve this. A heuristic control can be applied by moving each joint separately; or an inverse kinematic control can be applied by moving each joint simultaneously to place the end-effector to the desired position. There are two approaches in the second control method: the end-effector can go to the position entered from the computer directly, or it can go up/down, left/right and forward/reverse at a variable displacement to reach the desired position gradually.

While the RBMS works, it is very important to control the end-effector of the robotic arm. Inverse kinematics is used to determine the joint angles and the link positions given the desired position of the end-effector in space. There are two, algebraic and geometric, approaches to solve the inverse kinematics problem.

As illustrated in Figure 13, the robotic arm is controlled through the command input from the host computer. The control algorithm is written in MS QuickBasic4.5. A subroutine for calculating the inverse kinematics for the robotic arm position and orientation is used.

To improve the reliability of the robotic arm motion, another subroutine was introduced to allow the operator to move the end-effector up/down, left/right and forward/reverse by X inches, where X is a variable than can be changed at real-time.

Once the sandblaster starts, the manipulator travels from one end of the gantry table to the other, lowers down the nozzle 8 inches and returns to its starting location. This is one operating cycle. There could be several cycles depending on the surface area of the I-beams. The linear motion control software of the manipulator is similar to that of the robotic arm, as shown in Figure 12.

Figure 15 presents the hardware integration of the sandblast manipulator. The power plugs on the electro-hydraulic proportional valves for the containment system and for the robotic arm are parallel connected to the D/A board; the position potentiometer for the robotic arm is used as the feedback of the manipulator.

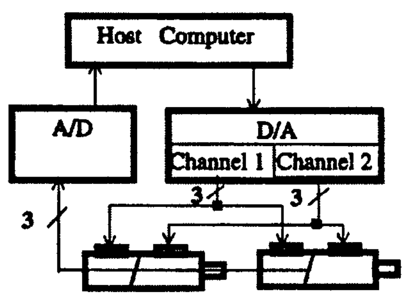


Figure 15: Sandblaster Manipulator Control Chart

5. CONTAINMENT SYSTEM

Since the system will be used to remove lead-based paint from steel bridge beams, a method of containing the toxic debris was needed. The containment box which was used with the RPRS (Figures 1 and 2) was completely redesigned for RBMS. That design used a large single box that was capable of containing one section of the beam, the web. The new design consists of two smaller, more flexible containment boxes as shown in Figure 16.

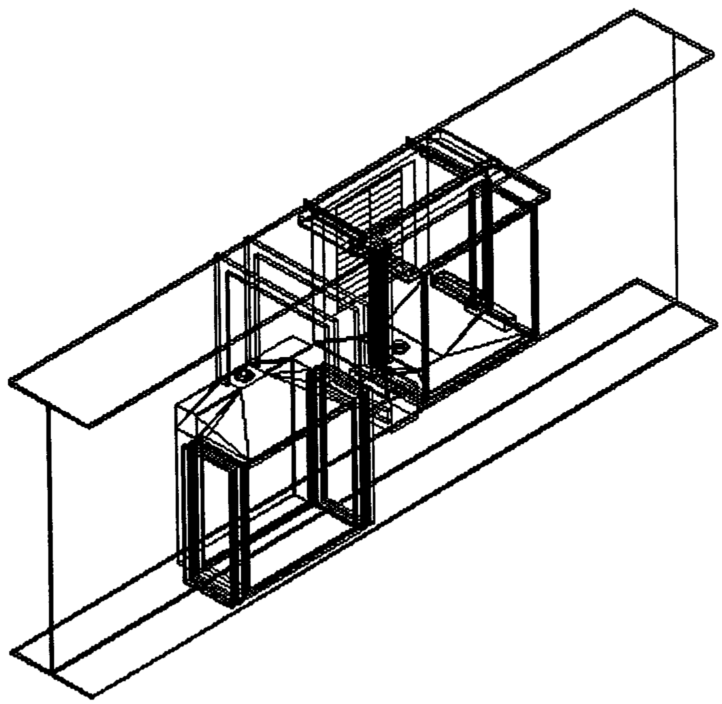


Figure 16: CAD Drawing of the Containment System

The modular design of the new 18" x 23" x 7" (45.7 cm x 58.4 cm x 17.8 cm) boxes provides more flexibility and more capability for the containment system. (see Figure 17) It is now possible to sandblast flanges (upper and lower) and trusses, because they can now be completely encased. The design of the dual box enabled the system to contain areas of the web that have drilled holes.

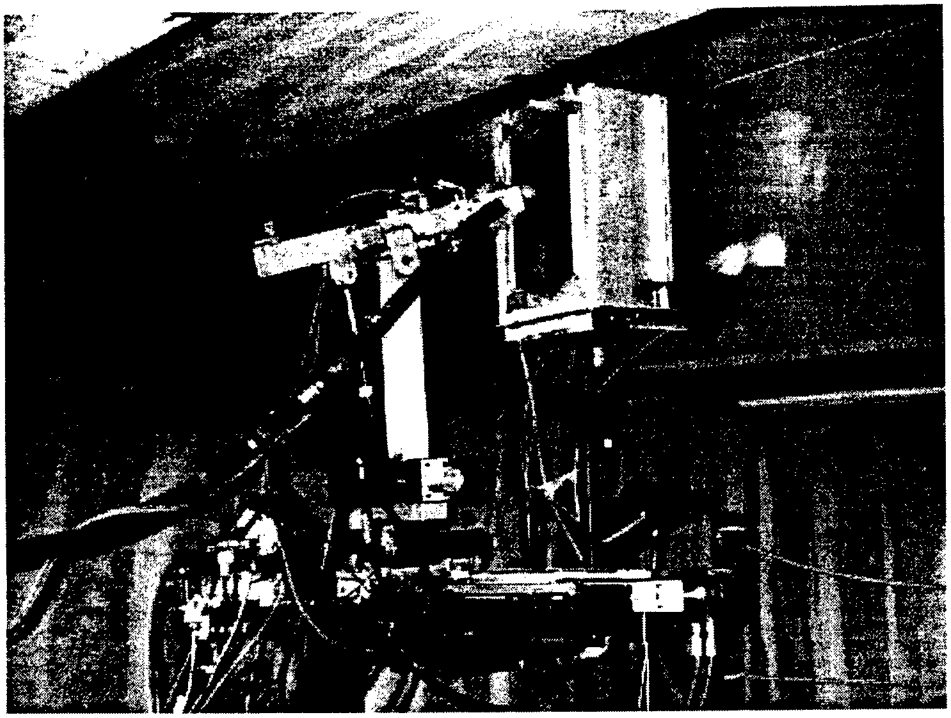


Figure 17: Overall System Deployed

The actuation of the containment system is both hydraulic and pneumatic. The primary (front) box utilizes two pneumatic cylinders and two pneumatic rotary actuators to change the location and orientation of the 7 inch (17.8 cm) nylon brushes used to seal the box against the I-beam. Two rotary actuators are mounted on the bottom of the box near the front pivot brushes, and are perpendicular to the web, creating a seal against the beam when the web is to be sandblasted. Additionally, the brushes can be rotated 180 degrees, resting on the outer side of the box. In this orientation, 2 inch (5.1 cm) brushes are available, pointing out to either side of the containment box. In this configuration, the system is capable of sandblasting in corners where the beam and a wall meet.

The two pneumatic cylinders, mounted inside the box near the top work simultaneously to extend and retract the top brush. The top brush is used to be able to sandblast the upper flange supporting the deck. In this case, it is not possible to seal the boxes around the flange therefore; the top brush is extended until it seals against the edge of the top flange. The pneumatic actuators are not proportional and do not have any feedback. They are only controlled by adjusting the air pressure entering the solenoids.

The sand and debris are evacuated from the box through a funnel system leading to a 6 inch (15.24 cm) vacuum hose that is mounted at the bottom of the primary box. The contaminates are drawn into this hose and brought back up to the top of the bridge using an 11 hp (8.2 kW) gasoline powered vacuum. This system provided adequate transfer of the particles from under the bridge, up to the bridge deck. In this prototype, the vacuum used did not contain any filtration devices. It was simply used to demonstrate the capability of the containment system.

The secondary (rear) box is used to catch sand and debris that goes through the trusses or below the flange. For this reason is was not necessary to actuate the brushes. For this reason they are simply fixed to the box. The secondary box is raised and lowered when necessary, and are clamped around the beam using a single hydraulic actuator and a proportional valve.

6. CLEANING AND PAINT REMOVAL

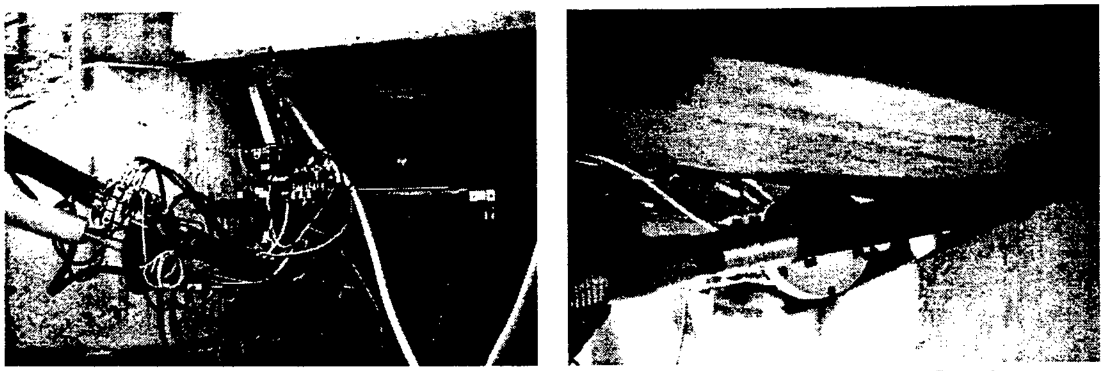
The maintenance procedure is accomplished by using the robot to manipulate existing tools. The tools presently used are a video camera, a high pressure spray washer, a sandblast nozzle, a needle gun, and a paint nozzle as shown in Figure 8. The motion of the robot is similar for each tool. Only minor differences exist. For example, when sandblasting and spray washing the path speed and distance from the surface are not critical. But, for robotic painting, speed is a critical variable to obtain a proper finish.

The first step in the maintenance process is to inspect the bridge. A video camera mounted on the robot (see Figure 5(a)) allows the operator to inspect the bridge and locate areas to be cleaned. The precise location of the spots can be documented based on information from the boom mounted encoders. Additionally, the video camera can be used to document the maintenance procedure.

During pressure washing, a high pressure water line is installed along the boom, attached to a 3200 psi (22 MPa) pump that is mounted on the bed of the truck. The universal gripper attached to the wrist is capable of picking up the pressure washer wand shown in figure 8. The pressure washer attachment is a wand with a quick release nozzle fitting. The outlet pressure and spray pattern are controlled by changing fittings. The robot can then be positioned and oriented in the desired manor in order to wash any part of the bridge.

When sandblasting, the nozzle (see figure 8) is attached to the gripper and the nozzle is inserted into the containment box (see figure 17). The nozzle and containment box are then run simultaneously. The nozzle is attached to a 1 inch (2.54 cm) hose fed by a sand drum and compressor from the top of the bridge. Sand was used as the medium for paint removal because it is the current means of paint removal used by NCDOT. Other methods of paint removal can also be used since the RBMS is capable of manipulating any type of tool.

As previously mentioned, the containment system is not capable of reaching every part of the bridge I-beam. For instance, a bridge bearing cannot be fully encased by the containment system. For this situation, a shrouded needle gun (see figure 8) is used. The needle attaches to the gripper in the same manner as the other tools and is pneumatically actuated. A solenoid switch is used to turn the needle gun on and off. A vacuum hose is attached to the top of the needle gun to contain any debris. The shrouded needle gun was specifically chosen because of its sleek design and the fact that the vacuum hose and air line both run from the back. This is advantageous since it makes it much easier to manipulate the tool into confined areas. The vacuum hose is attached to the same vacuum pump as is the containment system. A photograph of the RBMS manipulating the needle gun is shown in figures 18 (a) and 18 (b).



(a) RBMS Deployed to Clean Bearings (b) Needle Gun at Work on Bearing

Figure 18: RBMS Cleaning Bridge Bearings with Needle Gun

To demonstrate the adaptability of the RBMS to different tools, a carbon dioxide pellet accelerator developed by Oak Ridge National Laboratory was mounted to the robot arm as shown in Figure 19. This device accelerates dry-ice pellets to velocities of up to 350 m/s and 454 kg/hr. These high-velocity pellets impact a surface and in this case remove paint chips. The 20 HP (14.9 kW), 12,000 rpm centrifugal cryoblaster weighs about 100 pounds (45.4 kg), making it an ideal candidate for integration with a hydraulically actuated robotic system. Since the accelerator was much heavier than the other maintenance tools that were used, it was necessary to modify the robotic mount. In this case, the pneumatic gripper was not used since it was not capable of handling such a high payload. Instead, the accelerator was mounted to a plate bolted directly to the hydraulic wrist actuator.

Robotic manipulation is necessary because it is not possible for a human operator to carry the system due to the weight and operating speed of 9000 rpm. The two systems complement each other very well. Testing showed that the cryoblaster could be mounted and successfully run from this robotic platform. Paint was removed from a beam. Sand blasting still produces a more suitable surface, but the future looks bright for advancing the dry-ice blasting of steel.

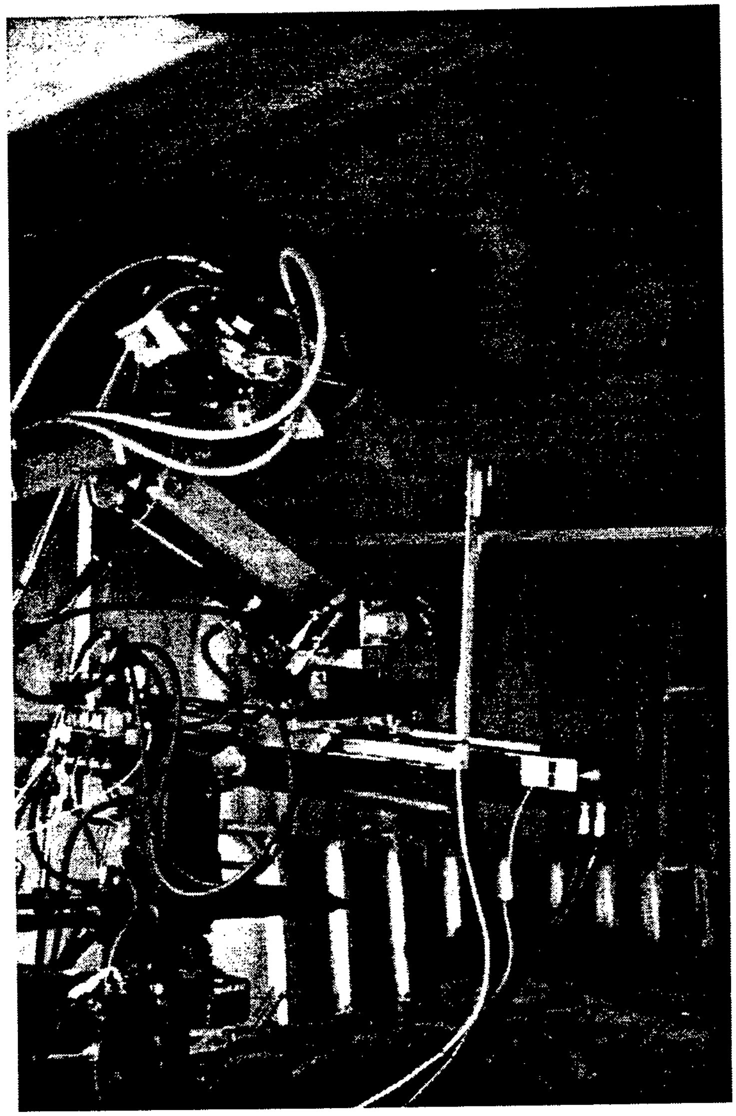


Figure 19: CO_2 Pellet Accelerator Mounted to the RBMS

7. ROBOTIC PAINTING SYSTEM

Paint on steel bridges is applied in a series of coats ranging from 1 to 6 mils. One mil is equal to one thousandth of an inch. Rarely does the total dry film thickness exceed 12 mils. A sheet of writing paper, for example, is approximately three mils thick. NCDOT requires four layers of coating on steel bridge surfaces. The first two are called primer coats, and the second two are called finishing coats. The minimum thickness of each layer is 1.5 or 2 mil. The coating thickness is one of the most important quality control parameters in steel painting operations. Each project specifies its own level of quality which is the minimum dry thickness that must be satisfied. Appearance is another important quality control parameter in the steel bridge painting operation. An appearance check ensures that the surface will not corrode more rapidly than expected. The major appearance failures include edge failure, dry spray, holidays or pinholes, and runs or sags [Painting Manual].

To consistently achieve the required thickness and appearance, the following aspects were investigated: 1) What are the parameters which affect the coating thickness and appearance? and 2) What are the values of the parameters to achieve the required thickness and appearance?

The process planning parameters for bridge painting operations were studied first. The purpose of this study was to determine whether or not the painting process planning parameters affect the thickness and appearance. Process planning is the fundamental step needed to sequence the individual task and to describe how a particular task will be accomplished [Chang et al. 1991]. For steel bridge painting operations, process planning is the function that establishes what parameters are to be used to paint a piece of steel bridge surface and achieve the specified quality (thickness and appearance).

In process planning for the paint application, a decision must first be made about how to set up the spray gun. By reviewing the literature and interviewing painting experts, a series of specific parameters was generated. They include: 1) spray gun angle, 2) type of spray gun tip, 3) air pressure, 4) fluid pressure, and 5) distance between the spray gun and the surface. The spray gun angle is the angle between the central axis of the spray gun and surface which needs to be painted. In order to reach the different areas on the steel bridge, the gun should be set up from different angles. If the area is a plane surface, the gun should be held perpendicular to the surface. If the area includes a right angle, the gun is set up around 45 or 135 degrees. The spray gun tip is chosen based on the viscosity of the paint which is a measure of the paint's ability to flow. The viscosity of the paint can be measured using a particular device.

Second, the spray gun path planning which describes how to move the gun should be decided during process planning. Two parameters, speed and path, describe the motion of the gun. One path pattern that the spray gun can move is a staircase path. This involves making parallel passes on the surface of the steel bridge until the entire surface is covered. In this research the staircase path is used because it is simple and easily performed. In order to generate the spray gun moving path, the width of the spray pass needs to be investigated.

Lab experiments were conducted to study how the process planning parameters affect the thickness and appearance. The experimental apparatuses include: 1) a Graco AA3000 automatic air-assisted airless spray gun, 2) a Graco pump, 3) a stepper motor, 4) a Centroid motion controller, and 5) a personal computer. Figure 20 shows the experimental facilities layout.

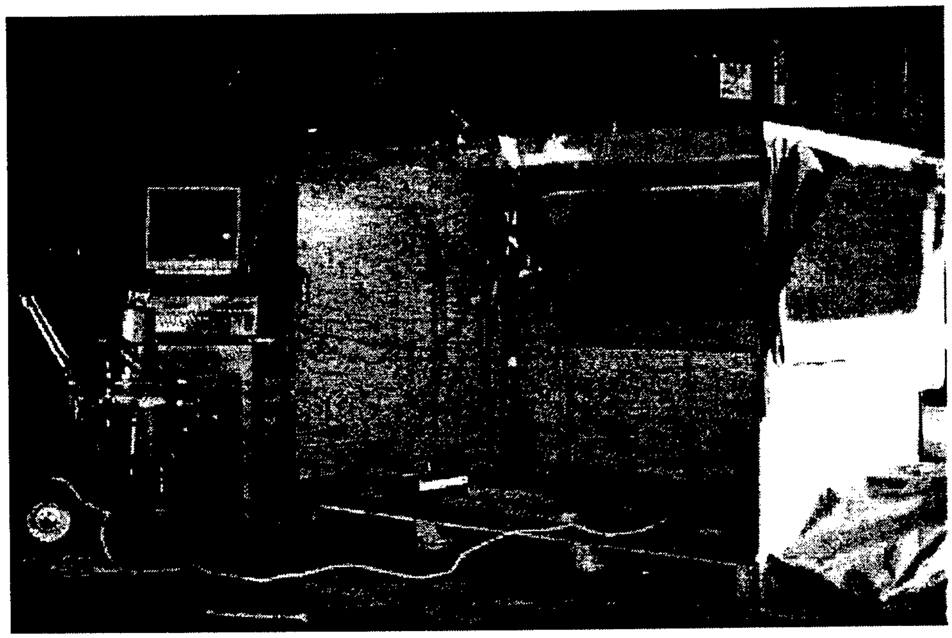


Figure 20: Experimental Facility at NCDOT Paint Shop

The initial experiments were performed on the plane steel surface. Results of the initial experiments showed that the process planning parameters (which are the gun angle, the air pressure, the fluid pressure, the distance, and the moving speed) have a strong influence on the coating thickness and appearance. To achieve the required quality, the spray gun should be set up perpendicular to the plane surface. Optimal values of the air pressure, the fluid pressure, the distance, and the speed are not easy to decide for the plane surface. However, the ranges of these parameters are known through the initial experiments. Air pressure ranges from 68.9 to 137.8 KPa (10 to 20 psi). Fluid pressure varies from 2067 to 3445 KPa (300 to 500 psi). Distance is from 20.3 to 30.5 cm (eight to 12 inch). Moving speed changes from 25.4 to 35.6 cm per-second (10 to 14 inch per-second).

In order to decide the optimal values of air pressure, fluid pressure, distance, and speed, factorial experiments were conducted. A factorial experiment is one in which responses are observed for every combination of factor levels [Freund et al.,1993]. In this research the responses are the thickness, the appearance, and the width of spray pattern.

The factors are the air pressure, the fluid pressure, the distance, and the moving speed. The air pressure, the distance, and the speed have two factor levels, which are 68.9 and 137.8 KPa, 20.3 and 30.5 cm, and 25.4 and 35.6 cm per-second, respectively. The fluid pressure has three levels which are 2067, 2756, and 3445 KPa. The number of levels are decided based on the fact that significant observations can be made at each factor level. The set of factor levels in this factorial experiment consists of all combinations of these levels (that is the 2 x 2 x 2 x 3 = 24 combination).

Experimental data analyses are performed using the multiple linear regression method. Regression analysis is a statistical method that uses a relationship between two or more variables so that one variable can be predicted or explained by using information on the others [Freund et al. 1993].

$$Y_t = 2.46 + 0.0014x_1 - 0.0092x_2 - 0.056x_3 - 0.069x_4 \quad \textbf{(Equation 1)}$$

Equation 1 is the regression model for the thickness. Y_t is the coating thickness, x_1 is the fluid pressure, x_2 is the air pressure, x_3 is the distance, and x_4 is the speed. The regression model for the width is shown in Equation 2.

$$Y_w = -9.75 + 0.0069\, x_1 + 1.5\, x_2 + 0.92\, x_3 - 0.12\, x_2\, x_3 \quad \textbf{(Equation 2)}$$

Y_w is the width, x_1 is the fluid pressure, x_2 is the distance, and x_3 is the speed. Since the coating appearance is good for all the experiments, there is no need to perform the analysis on the appearance. Table 1 shows the combinations which can be used to achieve the minimum thickness of 1.5 mil with 95% level of confidence. Table 2 shows the widths of these combinations. The authors have recommended that the air pressure, fluid pressure, distance, and speed should be set up at 137.8 KPa (20 psi), 3445 KPa (500 psi), 30.5 cm (12 inch), and 25.4 cm per-second (10 inch per-second), respectively, in order to achieve the required thickness of 1.5 mil with the probability of 95 percent. For this setting, the predicted width is 14.7 cm (5.8 inch) with 95% level of confidence. There is a general consensus that a probability of 95 percent gives a good indication of the overall effectiveness of an operation in the construction industry [Oglesby et al. 1989].

The concept of "feature" is used in many different fields. However, a unified definition of features does not exist [Fu et al. 1993]. There are form features (also called shape features, or geometric features), design features, and manufacturing features. In other words, the definition of a feature is application-dependent. The appearance of features has a strong basis in the geometric domain, therefore, it is acceptable to assume that “feature” can be interpreted as a geometric form.

Table 1: Predicted Thickness With 95% Level of Confidence

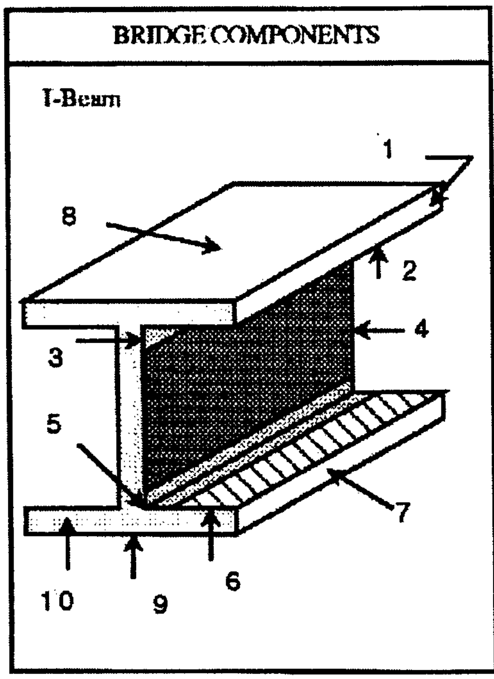
Test Number	Fluid Pressure (KPa)	Air pressure (KPa)	Distance (cm)	Velocity (cm/sec.)	Measured Thickness (mil)	Predicted Thickness (mil)	Lower 95% (mil)	Upper 95% (mil)
3	3445	137.8	30.5	25.4	1.6	1.6	1.5	1.7
6	3445	137.8	20.3	25.4	1.7	1.8	1.7	1.9
7	3445	68.9	20.3	25.4	2.1	1.9	1.8	2
10	2756	68.9	20.3	25.4	1.8	1.8	1.7	1.8
12	2067	68.9	20.3	25.4	1.6	1.6	1.6	1.7
15	3445	68.9	30.5	25.4	1.6	1.7	1.6	1.8
19	3445	68.9	20.3	35.6	1.6	1.6	1.6	1.7
22	2756	137.8	20.3	25.4	1.8	1.7	1.6	1.8

Table 2: Predicted Width With 95% Level of Confidence

Test Number	Fluid Pressure (KPa)	Air pressure (KPa)	Distance (cm)	Velocity (cm/sec.)	Measured Width (cm)	Predicted Width (cm)	Lower 95% (cm)	Upper 95% (cm)
3	3445	137.8	30.5	25.4	15.2	14.7	12.3	17.4
6	3445	137.8	20.3	25.4	12.7	12.2	9.7	14.9
7	3445	68.9	20.3	25.4	12.7	12.2	9.7	14.9
10	2756	68.9	20.3	25.4	10.2	10.4	8.4	12.8
12	2067	68.9	20.3	25.4	10.2	8.6	6.2	11.4
15	3445	68.9	30.5	25.4	10.2	14.7	12.3	17.4
19	3445	68.9	20.3	35.6	12.7	11.5	8.9	14.1
22	2756	137.8	20.3	25.4	12.7	10.4	8.4	12.8

In this research, features are defined as meaningful abstractions of geometry that can be used to reason about the spray painting processes. This means that one can find a set of process planning parameters that are needed to set up and move the spray gun based on a given feature. In other words, each feature corresponds to a set of parameters which include: 1) the spray gun angle, 2) the air pressure, 3) the fluid pressure, 4) the distance, 5) and the speed. For different features the values of the process planning parameters are different. A steel bridge can be represented by different features.

To create a feature "catalogue" for the steel bridge, bridge design drawings provided by the NCDOT's Bridge Maintenance Department were studied. The highway steel bridge structure was organized into four basic components: 1) beam (or girder), 2) bracing, 3) bearing, and 4) connections. In cooperation with the engineers at the NCDOT Bridge Maintenance Unit, basic features for each of the four components were developed. The optimal values of the parameters for each feature are being investigated using experimental method. Although it is impossible to include every highway steel bridge feature at this point, new features can be added to the list later. Examples of the I-beam features are shown in Figure 21.



FEATURES	
NO.	NAME
1	Top-Flange-Edge
2	Bottom-of-Top-Flange
3	Beveled-Top-Corner
4	Web-Surface
5	Beveled-Bottom-Corner
6	Top-of-Bottom-Flange
7	Bottom-Flange-Edge
8	Top-Flange-Surface
9	Bottom-Flange-Surface
10	Edge-End

Figure 21: Feature Characterization for a Bridge I-Beam

The painting operation of the system requires precision of the robotic arm. Specific tolerances are given for the different paint layers from primer to top coat. These are controlled by nozzle to surface distance, nozzle speed across surface, and air pressure for spraying. The first two conditions are controlled by the programming and the third is determined by an air pressure regulator set for the given paint that is adjustable at the truck. The air lines and paint lines were run along the crane boom and attached to a paint source and an air compressor both mounted on the bed of the truck.

8. IMPLEMENTATION

Implementation of the prototype RBMS will require private industry to develop a production unit. Since the system is essentially the robot mounted on the end of the crane, little is needed in terms of modifications to the truck crane. The system can be mounted on any type of truck crane due to this factor. Truck modifications require only the routing of the hydraulic hoses and electrical wiring.

In order to build a production unit of the robot, some redesigns and hardening will be required. For instance, the routing of the hydraulic hoses for the hydraulic actuators as well as the feedback cables should be changed so that there is no chance of breakage. The manner in which the hoses and feedback cables were run on the prototype made them easily accessible for modifications but they were also susceptible to being damaged. Ideally, both the hoses and cables should be routed inside the hollow links of the robot.

The control algorithm and concept of the use of a robot was successful and should be implemented in a straightforward manner. For use in the field, the algorithm needs to be embedded into a standalone black box system. The desktop computer must be eliminated. The process controls developed for spot cleaning, sandblasting, spray washing, and painting can be implemented directly. The methods for these tasks have been developed and the relationships between quality and robot parameters have been completed. The parameters described the robot settings as well as the tool settings. For example, for the robot these include orientation of the robot with respect to the beam and speed of the robot. For the painting procedure, these would include spray gun angle, type of spray gun tip, air pressure, fluid pressure, and distance between the spray gun and the surface.

Because of the costly and dangerous nature of the bridge maintenance procedure, it is very likely that industry would further develop this type of system. This was shown by the interest of private industry in phone calls to CARL, industry presence at the frequent demonstrations conducted, and the positive responses during the demonstration at the SSPC convention in Charlotte, NC in October of 1996.

9. CONCLUSION AND RECOMMENDATIONS

This report describes the development of the Robotic Bridge Maintenance System jointly developed by the NCDOT and CARL at NCSU. The system allows an operator to be removed from the dangerous environment under the bridge deck and allows him/her to tele-operate the entire bridge maintenance procedure.

One of the major advantages that this system has over others is that it has been designed as a relatively simple modification to existing equipment. The tracks and robot mount directly to the under bridge crane with four bolts and four quick connect lines. This also has the advantage of making the system easy to transport. Another advantage is the use of a robot to perform the tedious bridge maintenance procedure. By using a robot and a universal gripper, virtually any type of blasting method can be used. Additionally, the robot can be used for other types of applications in which a tool needs to be manipulated, and it is desirable to place the worker at a safe distance.

The retrofit of the RPRS system was successful. It was possible to integrate all of the additional capabilities required for bridge maintenance into one robotic system. There were still some limitations of the current prototype. The crane control should allow for spatial integration of multiple hydraulic sources. The hydraulic pump which controls the crane boom was set up for sequential control of the cylinders. For this reason, it was not possible to smoothly control the end of the boom by actuating all of the cylinders simultaneously. Modifying the truck's pump would provide a much smoother deployment.

The human-machine interface which was used is not adequate for an operator. The interface should be developed in a manner which makes it easily adaptable to different control set-ups for different operator skill levels and desires. For instance, some younger operators who are comfortable with video games may prefer using a joystick interface instead of a keyboard. An operator training procedure also needs to be developed to maximize the effectiveness of the system. The off-line simulator and overlay control method developed during this project worked well with the operators tested and is a good start for the final interface.

The robot and articulated platform worked well together. The redesign of the robot arm to a 150 lb. payload capacity allowed for flexibility of the system to use many different types of tools, for instance, the CO_2 blaster. This is important since due to the weight and operating speed of the Cryoblaster, it is impossible for a human to operate it. It must be done robotically. The need to use hydraulic actuators on the robot to obtain the desired payload capacity made cable management a problem. The robot needs to be redesigned to make it easier to route the hydraulic hoses. It may be possible to design the robot so the hoses can be routed inside the arm eliminating some problems.

The scheme for visual control for spot-cleaning turned out to be an excellent strategy. Allowing for the capability of cleaning small areas of the bridge without having to encase the entire structure is a cost-effective means of bridge maintenance.

The main problem encountered when cleaning bridges is the containment of the lead-based paint residue. The idea of using a "clamshell" type containment system consisting of two boxes has been shown to have much promise. Containment of all the debris is still a problem that needs more investigation. With the current design it was possible to contain most, but not all of the sand and debris. Rubber seals were added to the nylon brushes to improve the sealing capability of the boxes. This idea worked very well. It is recommended to try a combination of nylon brushes, rubber seals, and rubber inflatables to completely seal the box to the beam.

The other tools used during this project showed much promise for integration with the prototype. The CO_2 blaster worked well in removing paint chips, but it was not capable of removing rust from the beam. The blaster would work very well with a follow-up system, such as a sandblaster to remove rust, or as a stand-alone system when it is desired to only remove the paint without altering the surface. Additional work is also needed for a containment system. (It was not possible to use the containment box because the blaster nozzle was too large.)

The needle gun was shown to work well for contained bearing cleaning. Research is still required in developing a process control for the procedure. The painting and spray washing systems were very successful.

Finally, it is very important to note that collaboration between CARL, NCDOT, and ORNL was critical to the success of the project. Without it, it would not have been possible to obtain the level of success achieved.

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