Robotic Bridge Maintenance System: A Comprehensive Study

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ABSTRACT

Bridge maintenance is a matter of serious concern these days. Conventional system of employing workers for maintenance has become obsolete since it is unsafe, lacks quality and increases the time and cost of maintenance. This issue demands a new approach or system for the maintenance of bridges. Thus, robotic systems for bridge maintenance have advanced dramatically over the past few years. With a Robotic Bridge Maintenance System (RBMS) various maintenance activities such as pressure washing, crack detection, sand blasting and painting can be done more efficiently than the conventional system. In addition, this system can be used to build the 3D map of the bridge structure, to identify the different bridge materials, to determine the best suitable collision free paths etc. Thus RBMS ensure safety, reduce cost and time for maintenance and ensure maximum quality in maintenance. It is presently used as a better alternative to the conventional system. The focus of this report is to present an overview of this developed system and highlight its potential.

Key words: Bridge maintenance, sand blasting, robot, environment, RBMS, collision

1. INTRODUCTION

Bridges are essential in transport infrastructure worldwide. They facilitate the safe, effective and reliable access and movement of people and goods over streams, roads, railways and other obstacles. They are critical links in the transport network, benefiting communities and facilitating the growth of the National and State economies. Bridge maintenance is a critical responsibility. Failure to properly maintain bridges has resulted in abrupt bridge collapses; for instance, the Songsu Bridge collapse in Korea in 1994 and the Minneapolis Bridge collapse in the US in 2007 [Je-Keun et al. (2009)].

Steel bridge maintenance operations are dangerous and hazardous to human health. A typical maintenance operation involves sandblasting the bridge surface to remove old paint and rust, painting to protect the surface from weathering, spray washing and inspection of cracks. These works are 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 in US, 70% of all serious injuries to coating workers are caused by falls [Steven Lorenc et. al. (2000)]. Strenuous working conditions and worker fatigue contribute to an inconsistent quality of the applied painting. This hazardous maintenance procedure is therefore well suited for automation.

Development of Robotic Bridge Maintenance System (RBMS) is justified by the potential improvements in safety, quality, and productivity. With a Robotic Bridge Maintenance System, human operators can be removed from the dangerous work environment location under the bridge deck to a safe place on top of the deck. There they can teleoperate the robotic system without risking their health or their lives. The quality of painting will also be improved because the robotic system does not suffer from exhaustion or fatigue as a human operator does and productivity can simultaneously be greatly improved. Since no scaffoldings are required and number of workers involved in the maintenance activities is reduced, RBMS proves more economic than the conventional system employing human workers for maintenance. A consistent, high quality painted surface in a less time is also achieved. More over advanced robotic techniques for bridge structure map building, material type classification, collision avoidance, etc. have also been developed.

This paper presents the implementation of this robotic system, its design aspects, maintenance activities and issues related to the development of the system.
2. OVERVIEW OF THE SYSTEM
The original prototype of the system was developed and successfully tested as a robotic bridge paint removal system in August of 1994. The system has been since upgraded to perform other tasks. Presently the RBMS has four main capabilities: (i) Remote inspection, (ii) Spray washing, (iii) Sand blasting, and (iv) Painting.

As shown in Figure 2.1, the system is composed of a bridge-inspection crane (Peepcrane) with a crane boom, an actuated platform, hydraulically actuated robot arm with maintenance tools, a containment enclosure with a vacuuming system, and a vision system and distance sensors. The crane boom is made up of three sections of which the third section was retrofitted. The actuated platform was built for positioning the robotic manipulator and the enclosure with two linear sliding tables. Joysticks are used to activate the crane boom and the actuated platform. A Mitsubishi 6 degree of freedom micro robot arm is used to which various maintenance tools are being attached. Tools include needle gun, sandblast nozzle, spray paint gun, pressure washer etc. selection of which depends on the work involved. The dust containment enclosure has a brush opening that allows the robot arm to insert the nozzle and perform abrasive blasting. The vacuum system removes paint debris and blast material from the enclosure. The two sliding tables provide independent linear movement for the robot arm and the enclosure parallel to the beam surface. The vision system is made up of a television monitor, camera, and a frame grabber. Ultrasonic sensors are mounted on the containment enclosure to measure the distance between the edges of the box and the steel beam [S Moon et al. (1997)].

3. IMPLEMENTATION OF RBMS
The procedure to implement the RBMS begins with the deployment of the crane. If a Computer Aided Design (CAD) drawing of the bridge is available, the crane can be deployed 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 teleoperate the crane using two video cameras: one mounted on the arm of the robot and a second camera placed on the bridge to observe the crane.

Once the crane is deployed underneath the bridge, a sonar system, consisting of sonars mounted to the crane boom, the robot, and the containment system, is used to position the robot within an acceptable range to the bridge beam. The acceptable range is defined by the work-space of the robot. With the robot positioned under the bridge, the maintenance procedure can proceed. The robot can now be controlled to inspection, spray wash, sandblast, and/or paint the beam.

Some examples of bridges where RBMS has applied are: (1) Sydney Harbour bridge in Australia and (2) Honshu Shikoku bridges in Japan.
4. PARAMETERS FOR SYSTEM DESIGN

4.1 Environmental Awareness

At the start of a bridge rehabilitation project the robot systems do not have any knowledge of the bridge environment. The knowledge required for the robot to operate in bridge environment could be given by providing CAD drawings of the bridge. However, many old bridges that need maintenance do not have CAD drawings. Therefore, a sensor network attached to the robot that could build the geometrical 3D map of the complex structural environment has been developed.

4.2 Exploration and 3D map building

Generally the surface geometry of a fixed bridge is static. The data for building a 3D map of the bridge components that needs to be maintained is sensed by the sensor system attached to the robot arm from a known spatial location. The robot collects the sensor data from different robot positions and robot arm poses. These data sets must be transformed to a single global coordinate frame prior to incorporation in a three dimensional map of the environment. The robot arm carries the sensor package. Then the data collected from different locations will be combined using advanced simultaneous localization mapping (SLAM) techniques to form a 3D map.

A Hukuyo laser range finder is used to sense the environment as shown in Figure 4.1(a). Appropriate exploration strategy can then provide a dense 3D point cloud as shown in Figure 4.1(b) from which the geometry of the steel structure can be extracted [D.K Liu et al. (2008)].

![Figure 4.1](image)

**Figure 4.1** (a) Scale model of the target bridge environment. (b) Resulting point cloud map

4.3 Material Type Classification

In a bridge structure it is common to have many material types such as steel, timber, concrete and plastic pipes. Therefore it is necessary for the system to clearly identify the material that requires maintenance from other materials present in the environment. Preliminary experiments showed that the visual appearance of the bridge structural environment is ambiguous with similar color/texture areas occurring in different parts of steel, wooden or concrete structures indicating vision only discrimination may not be possible.

A capacitive-based sensing approach, the Adaptive Capacitive Sensor for Obstacle Ranging (ACSOR), has been investigated for obstacle ranging. Capacitive sensors are insensitive to lighting, noise, color, shape, surface and texture of the obstacles. The ACSOR has been fitted with a noise and stimuli response analyzing algorithm allowing the sensor to determine the material type of a sensed object [D.K Liu et. al. (2008)].

4.4 Robot path/motion Planning

Planning of the robot motion is conducted after the map of the environmental is built and the areas to be blasted have been identified. Path and motion planning must attempt to maximize the maintenance coverage completeness, minimize the movement of the robot arm and the support platform and maximize efficiency/productivity. So generic algorithms have been developed to determine the best possible consequential path and motion to blast the surfaces to achieve predetermined surface finish standard.

4.5 Collision Avoidance

Collision detection and avoidance during maintenance operation is a crucial and difficult problem that has to be solved. A capacitive sensor for collision detection has been developed and a sensor network distributed
around the robot arm for collision prediction is being developed. Simplifying the geometry of the robot and its environment by approximating it with a series of spheres was found to be very effective for collision detection. Figure 4.2 shows how spheres enclosing the robot and the environment are used to detect collision based on a distance query method.

![Figure 4.2 Collision Detection](image)

For collision avoidance, a three-dimensional force field (3D-F²) method for efficient collision avoidance of the 6DOF manipulator in complex blasting environments while keeping the planned nozzle’s path and speed unchanged has also been studied. The 3D-F² is defined as ellipsoid shapes covering selected links of a manipulator by using the information from the capacitive sensor network. When the manipulator moves and its ellipsoid force field approaches an obstacle in a defined range, a repulsive force will be generated and considered in the robot kinematic and dynamic analyses.

### 4.6 Selection of a robot

The selection of the robot for grit blasting was based on the orientation versatility, high speed movements, repeatability and load-handling capability. The robot is mounted on a movable platform giving the prototype system the ability to perform environment exploration and mapping, material type classification and grit-blasting over the majority of the bridge as shown in figure 4.3.

![Figure 4.3 A prototype robotic system](image)

### 4.7 Human Robot interface

1. Manual Mode allowing full operator control - In some complicated locations within the bridge structure only manual mode will be suitable.
2. Semi-Autonomous Mode enabling some control by the robot but specifying the defined region where the robot will blast.
3. Autonomous Mode meaning that the robot will be automatically able to commence mapping and blasting in a new uncomplicated part of the bridge with minimal operator involvement.

### 5. MAINTENANCE ACTIVITIES

The maintenance procedure is accomplished using the robot to manipulate existing tools. Figure 5.1 is a photograph of the different maintenance tools currently used. From top to bottom: needle gun, sandblast nozzle, spray paint gun, and pressure washer.
Figure 5.1 Maintenance tools

5.1 Pressure washing

For pressure washing, a high pressure water line is installed along the boom and connected to a 22 MPa pump mounted on the bed of the truck. The pressure washer attachment is a wand with a quick release nozzle fitting. Changing fittings controls the outlet pressure and spray patterns. The universal gripper attached to the wrist is capable of picking up the pressure washer wand shown in Figure 5.2. The robot can then be positioned and oriented in the desired manner in order to wash any part of the bridge.

Figure 5.2 Pressure washing in action

5.2 Crack Detection

For crack detection a bridge inspection robot system equipped with machine vision is proposed. The machine vision system takes images as inputs and produces other types of outputs, such as crack lengths, crack widths and an outlined sketch of the bridge status. [Je-Keun et al. (2009)].

Figure 5.3 Entire image processing flow chart

5.2.1 Capture

As a first step, image of the bridge structure is captured by using a machine vision system composed of a charged couple device (CCD) camera, a digital video recorder (DVR) board and a vision processing program on the server computer.

5.2.2 Pre-processing

In this process, captured image is enhanced through the removal of artifacts using several median filters. Noise or any other impurities if present in the image is removed in this process to get the smoothed image.

5.2.3 Crack detection and tracing

In this process, the smoothed image is analyzed to detect the presence of cracks by an crack detection algorithm. If a crack is detected, crack tracing algorithm calculates the length and width of the crack. In some cases, the crack detection result from the blurred images does not guarantee the accuracy of the crack.
information. Moreover, it is hard to retake a picture in the same position. Thus an image de-blurring process technique is applied to improve the detection result.

5.2.4 Post-processing
In this process, each crack image is sequentially stitched for one panorama image. And then, the panorama images including the information of entire crack lines are converted into the file format (here, the dxf format compatible with CAD file) required for the bridge management system (BMS).

5.3 Removal of rust
Rust is removed by the process of sand blasting. First step is to decide whether blasting is to be performed or not.

5.3.1 Color space conversion
Image of the surface is taken and color space conversion transforms the input image from the red/green/blue (RGB) color space to the hue/saturation/intensity (HSI) color space. The values of colors in the RGB color space are subjected to deterioration owing to changes in illumination. But Hue and saturation are related to color, or chromaticity, and are illumination independent components.

5.3.2 Classification of rust area
The J48 decision tree algorithm classify each pixel in the test images as either rust or background [Hyojoo Son et.al.(2014)]

![Flowchart](image)

**Figure 5.4** Proposed automated process for determination of rusted surface areas to be blasted.
5.3.3 Determination of blasting area

First, the percentage of rust in the image was computed, by calculating the ratio of the number of pixels classified as rust to the total number of pixels in the image. If less than or equal to 0.3% of the pixels in the image contain rust, the final decision—that blasting is unnecessary—is made immediately, without further processing. If greater than 33.0% of the pixels contain rust, the final decision—that blasting of the entire surface shown in the image is necessary—is made immediately, without further processing. If the percentage of pixels that contain rust is greater than 0.3%, but does not exceed 33.0%, the rust distribution type should be further considered before a final decision is made [Hyojoo Son et.al.(2014)].

As shown in Figure 5.5 rust distribution types are divided into three groups: spot, general, and pin-point rusting. Spot rusting consists of rusting concentrated in a few localized areas. General rusting consists of rusting with rust spots of various sizes and shapes that are randomly distributed across the surface. These two types of rusting have characteristics that occur locally in a few areas; therefore, blasting is necessary only in the rusted areas. Pinpoint rusting consists of small, isolated spots of rust that are distributed across the entire surface shown in the image. This indicates that corrosion has spread across the entire surface. Blasting of the entire surface is necessary because without it corrosion would continue to occur.

![Figure 5.5](image)

(a) Spot rusting, (b) General rusting, (c) Pin point rusting

After blasting area is determined, sandblasting nozzle is attached to the gripper and is then inserted into the containment box. Sand is thrown at a high velocity to the surface. It impacts the work surface and rebounds taking rust and old painting with it as shown in Figure 5.6.

![Figure 5.6](image)

5.4 Painting

Painting requires precise motion of the robotic arm. The coating thickness and appearance are used to measure the quality of steel bridge painting. The parameters that were used for painting process planning are: (1) spray gun angle, (2) air pressure, (3) fluid pressure, (4) distance from the paint nozzle to the surface, and (5) moving speed.

These parameters were found to have a strong influence on the coating thickness and the appearance. Lab experiments were conducted to determine the optimal values for different bridge features which were created to represent the steel bridge. Each feature corresponds to a set of optimal values of the process planning parameters. Using these optimal values to set up and move the spray gun, the specified quality can be achieved. The spray gun that was used was an automatic air-assisted airless spray gun. 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.
6. DEVELOPMENT ISSUES

6.1 Blasting nozzle reaction force reduction

In sand blasting, the blast sand is forced through the blast nozzle at very high velocity which generates a reaction force up to 88 Newton in the opposite direction of the sand flow [D K Liu et al. (2008)]. To address these limitations, a force transfer mechanism is being developed for reduction of the blasting reaction force. Figure 6.1 shows the mechanism which uses internal pressure of the compressed air from two small delivery hoses to generate a force pushing the nozzle in the opposite direction to the blasting reaction force. The rigidity of delivery hoses deflects the majority of the reaction force through to the hoses to a fixed anchor point.

![Figure 6.1 Sand blasting reaction force and a mechanism for force reduction](image)

6.2 Requirement of large quantity of sand

Sand blasting requires very large quantity of sand. Therefore a carbon dioxide pellet accelerator developed by Oak Ridge National Laboratory was mounted to the robot arm. This device accelerates dry-ice pellets to velocities of up to 350 m/s [S J Lorenc et al. (2000)]. These high velocity pellets impact a surface and in this case remove paint chips. 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 gripper was not used since it was not capable of handling such a large payload. Instead, the accelerator was mounted to a plate bolted directly to the hydraulic wrist actuator. This technique also eliminates the need to contain and separate the large quantities of sand needed to blast an entire bridge.

Other issues are:

1.Operational safety of the system and of people around the blasting environment.
2. Protection of the robot system, including the moving platform, from fine dust and lead particle poisoning.
3. Vibration of the robot arm when coupled with the grit-blasting device and its effect on grit-blasting quality.

7. CONCLUSION

Bridge maintenance is one of the largest expenditure items in traffic infrastructure development and maintenance. Robotic Bridge Maintenance System can perform the various maintenance activities of the bridge – inspection for cracks, spray washing, removal of rust, painting etc in more efficient and economical way. In addition, RBMS also develops the 3D map of the bridge structure, classifies and identifies the different materials in the bridge, evaluate the degree of rusting and many more as reported. The process of maintenance of bridge is thus automated. It does not risk the life of workers involved in the maintenance activities. Also it ensures safety, shortens maintenance time, reduces costs and most importantly ensures the quality in maintenance. Robotic bridge maintenance system thus proved to be a better alternative to the conventional system employing human workers for the maintenance activities.
8. REFERENCES
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