Robotic System for Searching Cracks beneath Bridge

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Abstract This paper proposes a robotic system for searching cracks beneath bridges. This robotic system for bridge inspection has been developed with aims of checking the safety status of a real bridge and gathering accurate data such as crack widths and lengths. The developed robot system is composed of the moving mechanism mounted on a specially designed car and the vision system for precise inspection. Especially, this paper emphasizes the system integration method to design and control the entire robot system.

Keywords Inspection robot, Crack detection, Vision system, Bridge inspection.

1. Introduction

The number of bridge construction has been gradually increased in Korea as shown in Fig. 1. According to the increase of bridge construction, the number of bridges to be inspected has been annually increased at the same time. Now, approximately 12,000 bridges should be inspected for safety test every year according to the report suggested by [1]. Generally speaking, it is more economic to maintain and repair the existing bridges rather than the construction of new bridges, although the maintenance and repair cost of bridges rapidly increases every year in Korea. For instance, comparing to the maintenance cost of bridges spent in 1995, it showed 200 times increase for 10 years. Thus it has been more and more necessary for the efficient and economical method to maintain the bridges.

Although the robot technologies have advanced in a variety of industrial areas, the robot application technologies for the safety diagnosis and maintenance of real bridges have lagged behind. Currently, the bridge inspection and maintenance have been manually conducted by the educated inspection workers in poor surroundings [2, 3]. As a matter of fact, the inspection workers check the safety status beneath the bridge only by counting the number of cracks, measuring the maximum width of the crack line and taking pictures. Thus the accuracy and quality of safety report become greatly different according to the diligence of inspection workers. Also, since the bridge inspection is performed outdoors, especially beneath the bridge, there can be problem concerning the safety of inspection workers. Inspection workers stand on temporary scaffolding in order to inspect the safety status of bridges [4, 5].

An industrial disaster can be always caused during the manual inspection. Also, the absence of the safety device can cause it in performing the bridge inspection. So, the improvements of working environment have become the first consideration in bridge inspection. Hence, there is a necessity to develop the bridge inspection robot system by using the unmanned robotic technologies. An inspection robot is the most useful when it can carry sensors into inaccessible or hazardous areas, thereby making the task safer for the inspection workers [6]. For example, the robot system for the underwater inspection of the bridge piers has already been developed in [7]. In this paper, we aim at raising the consistency of inspection results, improving the exactness of annual safety reports about the bridges, and reducing the industrial disasters. With these aims, we will suggest a robotic system for detecting cracks with vision and various sensors.

This paper is organized as follows; the section II describes the total robot system to be suggested; the section III suggests the image processing algorithm for detecting cracks; the section IV shows the integration method for the total system; and the section V shows the experimental results; in the end, we draw the concluding remark in section VI.

2. Total System for Bridge Inspection

2.1 Overview
The total system for the bridge inspection consists of a specially designed car and the inspection robot mounted on an end-point of a specially designed car as shown in Fig. 2. This multi-linkage mechanism was designed for dispatching the inspection robot system under the bridges [8]. And the inspection robot can detect the cracks beneath the bridge.

Fig. 2. Overview of total system for bridge inspection

Last link of the multi-linkage is able to be stretched to the maximum 12[m]. So, we have to consider the weight of the inspection robot to reduce the vibrations which can be caused in the cantilever beam. Otherwise, the last link will be deflected and oscillated according to the movement of the inspection robot system. After solving the corresponding beam equation, we found out that the weight of the inspection robot system should be less than 30[kg] to minimize the vibration and deflection problems. So, we have designed the inspection robot system as light as possible, to be about 20[kg].

2.2 Mechanism of Inspection Robot

A. Mechanism for pan/tilt movement

The environment under a real bridge is neither constant nor, for example, the wind can cause the swing motion of the multi-linkage. In this case, the multi-linkage is shaken and bent by the external environmental disturbances. In order to deal with these kinds of unknown disturbances, we equipped laser the sensor and the gyro sensor to the tilt mechanism for maintaining the horizontality as shown in Fig. 3. Gyro sensor is concerned about the horizontality. In our robot system, controller receives the data from gyro sensor, and control the pen/tilt mechanism to maintain the horizontality.

There are two motors on pan/tilt mechanism. And pan/tilt mechanism rotates to maintain horizontality with camera, laser sensor and gyro sensor. Pan/tilt mechanism has to stand the load, but if it pan/tilt mechanism has to rotate so fast to maintain horizontality with a camera, laser sensor and gyro sensor, it would difficult to stand the load. So we tested a lot to make this system stable.

B. Mechanism for gravitational direction movement

We have designed this mechanism with two stages, because we had to reduce the weight of the inspection robot and make the inspection robot move higher as shown in Fig. 4. This two-stage mechanism was devised for further extension to about 1[m]. This system is efficient to reduce the weight and the number of motors. So, we can lift the pan/tilt mechanism with 1 motor and wires.

This mechanism can move the pan/tilt mechanism to specific position from beneath the bridge. In this robotic system, controller receives the data from laser sensor and controls this mechanism to maintain same distance from beneath the bridge while inspection robot inspects beneath the bridge.

C. Control system

This controller system has a velocity controller and position controller as shown in Fig. 5. And gyro sensor and laser sensor give controllers the angle and distance from the bridge. Each controller receives the data from sensors and controls the mechanism to stand horizontally and maintain the specific position against various disturbances.

Fig. 3. Mechanism for pan/tilt movement

Fig. 4. Mechanism for gravitational-direction movement

Fig. 5. Block diagram of controller system
We concentrated that controller should process the data in real-time. So, we used the DSP F2812 (manufactured by TI Co.) as microprocessor that is able to process the data in 150MHz. Also, this microprocessor has various and useful peripherals such as the CAN, SCI, ADC and so on.

3. Vision System

The purpose of the vision system is to detect cracks of bridge surface automatically from image inputs. The crack information can be used to maintain the bridge and to decide an appropriate rehabilitation method to fix the bridge with cracks. This information is very important for managing the bridge.

This vision system is composed of a Charged Couple Device (CCD) camera, a Digital Video Recorder (DVR) board and a computer[9, 10]. In order to determine the specifications for the vision system, the weight, electric power, communication scheme and cable width should be considered. The environment under a real bridge is not constant, for example, the wind can cause the swing motion of guide rail. In this case, the rail is shaken and bent by the external environmental disturbances. In order to deal with these kinds of unknown disturbances, we attached the driving motor and gyro sensor to maintain the horizontality. The CCD camera is remote controlled by RS-485. Therefore, the inspector uses the function of pan/tilt, zoom, and focus through PC. The inspector can control the pan/tilt to a desired angle, and can change the magnification of camera zoom. When the magnification of camera zoom is changed, the camera is focused automatically. Related algorithms for processing the images captured from cameras have been designed and implemented. Fig. 6 shows the process of vision system.

Vision system captures images every 200ms to operate inspection robot in realtime because total process of vision system takes 200ms. And capture, pre-processing, crack detection and post-processing are processed within 200ms.

![Fig. 6. Process of vision system](image)

After capture, vision system performs three steps of pre-processing for automatic crack detection. And then vision system performs the crack tracing to acquire the information of crack lengths and widths. Lastly post-processing of result is conducted to store the information into database and supervise it anytime. More detail explanations will be suggested in the following sections.

3.1 Crack Detection

Existing systems for crack detection simply display the detected cracks. However, for more effective bridge inspection, we also need some information about the crack assessment such as length or width of the cracks. In the crack detection, there are many problems such as irregularities in crack shape and size, various soiling and painted surfaces, and irregularly illuminated conditions. These may cause serious problems in automatic crack detection. In order to solve these problems, we propose the following method for automatic crack detection.

Our method consists of two steps: crack detection and crack tracing.

A. Crack detection

For the crack detection, we perform three steps of pre-processing and extract the candidate cracks.

Firstly, we subtract the smoothed image from the original image. The smoothed image is obtained by using a median filter [11]. The purpose of this process is to maintain a uniform brightness throughout the image and to effectively detect cracks in the shadows.

Secondly, we remove noises on the bridge surfaces using a filter for removing isolated points. Through this process, we can reduce the candidate cracks and the unnecessary search time.

Thirdly, we apply morphological operations such as dilation and thinning to guarantee the connection between crack segments, where the number of iterations is determined by the distribution of candidate cracks. After this process, we obtain the connected cracks from the original image.

B. Crack tracing

![Fig. 7. Procedure of Crack Tracing](image)
For the crack tracing, we divide the image with detected cracks into several regions and select a seed point in each region. Each seed point which has the maximum probability of being a crack in the region is selected. From a seed point as a starting point, the cracks are traced bidirectionally. For each seed point, we examine the intensities of 8-neighbor pixels to determine the direction of next pixel with the minimum intensity.

Fig. 7(a) shows the procedure for crack tracing. We decide the next pixel that has the lowest intensity of 8-neighbor pixels by equation (1).

\[ P_n = \min \{ \text{intensity of } P_i \} , \quad i = 1, 2, \cdots, 8 \quad (1) \]

In this process, the progress direction is replaced by \( D_n \) that is from \( P_{n-1} \) to \( P_n \). To avoid local minima, the range of direction is restricted.

While tracing the crack, we measure the width and the length of the crack at the same time. Fig. 7(b) shows the gray-level profile of an orthogonal line of the progress direction. Because the crack has lower intensity than the background, we can define the distance between two inflection points of second-order derivative as the width of the crack. Since the width of the crack is calculated in pixels, the final measurement is represented by the multiplication of the number of pixels and the pixel resolution. In order to improve the measurement accuracy, the width of the crack is calculated considering the gradient between the crack and the background. After the bidirectional tracing is finished, both of the cracks are merged.

### 3.2 Post-processing of the Results

#### A. Making the results into database

The results of crack detection are stored into database, in order to keep all the information necessary to maintain the bridge. The results of inspection are converted into an interchangeable file so that the results can be used in the Bridge Management System (BMS). The interchangeable file is stored in dxf format that is compatible with CAD files. The structure of the dxf file format is carefully investigated to parse the syntax of each component, in order to write the information of detected cracks into a dxf file. Fig. 8(b) shows the result of created dxf file.

Moreover, we should also be able to display the whole image of the results so that the defects in a wide area beneath the bridge can be examined at a glance. The detected cracks and the result of image stitching are shown in Fig. 8(a).

#### B. Supervised manipulation

It is very difficult to detect cracks automatically from noisy images of concrete surface. Therefore, some utility functions to support user’s manipulation are necessary for the accuracy of inspection. The proposed machine vision system can detect cracks in real time, and it also has some utility functions for supervised manipulation.

These functions include the capability for adding lines and polygons. If an inspector wants to add some missed defects such as cracks, water leakages and scars in the result, he can draw the shape of defects using polylines and polygons. Fig. 9 shows the result of adding defects by the inspector.

### 4. Integration for Total System

#### 4.1 System Integration

The multi-linkage system, the inspection robot, and machine vision system suggested in the previous sections should be integrated into the specially designed car. Also, the server computer as a total manager has to control the whole functions in real time as shown in Fig. 10. It is important for the server computer to be synchronized between the entire motion control system and the machine vision for the real time operation. The server computer sends the command signals to the motion control system composed of 5 DOF’s multi-linkage system and 3 DOF’s inspection robot and then receives the motion data signals whenever sending the command signals for communication handshaking through the CAN communication. Also, the server computer sends the command signals for the focal length and image capturing to the machine vision system through the RS-485 communication and then receives the image (640x480) data through the BNC cable. Finally, the total manager program in the server computer includes two sub-windows program; the one is for the motion control systems and the
other is for the machine vision system. So, the inspection worker through the total manager program can control the entire motion control system, watch the crack images beneath bridge and make the database for the annual inspection report on the driver’s seat.

4.2 Task Planning

Since each bridge has its own shape, the task planning is required in advance before performing the bridge inspection. The task planning for bridge inspection is shown in Fig. 11. For this, the distance between the bridge surface and machine vision system should be kept constantly for guaranteeing the constant perspective image, also, the orientation of machine vision system should be kept orthogonally to the bridge surface for guaranteeing the constant pixel resolution per image.

The maximum range of up/down motion is at most 1[m], however, the shapes of some bridges may be over this range. Then we should adjust the focal length to sustain the constant pixel resolution according to the focal length planning in advance.

5. Total Experiment and Conclusion

5.1 Experiment

We tested the pan/tilt mechanism first. Because environment under real bridges is not constant, we had to confirm whether pan/tilt mechanism can maintain the horizontality or not. So, we moved the multi-linkage up and down as shown in Fig. 12. And we confirmed that this pan/tilt mechanism always maintain the horizontality.

Finally, we have tested this robotic system beneath the real bridge as shown in Fig. 13. There were four supporting beams beneath this bridge. This test environment was conducted at a small bridge in Hanyang University in Korea, because it was difficult for us to test this system at big bridge without experts in charge of the bridge management. So, we are going to test at the big bridge with experts next time.

We have experimented three kinds of items in this environment. Firstly, we checked whether the mechanism for gravitational-direction movement can maintain the specific position or not. And we confirmed that this mechanism always maintain the specific position beneath the bridge. Secondly, we checked whether the tilt mechanism can rotate to detect cracks accurately at the supporting beam or not. As a result, we confirmed that this mechanism rotated 15 degrees each automatically at the supporting beam. Thirdly, we check whether vision system can detect cracks in real-time or not. As a result, This vision system can detect cracks in realtime with 200[ms] and display on the monitor.

In addition, we explained extra functions of vision system. Fig. 14 shows the result of crack detection. This window serves worker lots of information. Especially,
worker can confirm images of detected crack, crack widths, crack lengths and result of image stitching. And worker can control the camera through those buttons.

![Fig. 14. Result of crack detection](image)

We recorded all experiments and uploaded to our ftp server. So, you can see the experimental video clips through our ftp server [12].

6. Concluding Remark

The robotic system for unmanned bridge inspection has been developed for a real application. Till now, most bridge inspections have been manually done by counting the number of cracks, measuring their lengths and widths and taking their pictures. In this case, the quality and reliability of safety report on bridges can be subjective according to the inspection worker. In this paper we have shown that the suggested robotic system can be an alternative of the manual bridge inspection. The proposed bridge inspection system is composed of three main parts; a specially designed car, robot mechanism and control system for mobility, and machine vision system for the automatic detection of cracks. Ultimately, this robot system has been developed for gathering accurate data in order to record the annual changes of the bridge’s safety circumstances as well as checking the safety status of bridges. Finally, the effectiveness of the crack detecting and tracing algorithms was shown through a few experiments.

Acknowledgements

This work was supported by the BIRDI Program of MOCT (Ministry of Construction and Transportation) and KICTTEP, Rep. of Korea

References


[12] ftp://humanoid.hanyang.ac.kr