Design and Implementation of a Manipulator System for Roadway Crack Sealing

Guijie Zhu, Zhun Fan*, Wenzhao Chen, Yugen You, Sibo Huang,
Weixiang Liang, Runzhan Fu, Jiaming Xin, Jingming Chen, Furong Deng, and Youzhao Hou

***Abstract*— Crack detection and crack sealing are challenging tasks which have been researched for decades due to the complicated roadway conditions in real world. Especially, crack sealing is an important procedure used to extend the life of road pavement. This paper develops and implements a kind of manipulator system for roadway crack sealing, which consists of a six-degree-of-freedom(6-DoF) manipulator with a novel crack sealing end-effector, a stereo camera, an air pump, a glue barrel and a laptop. The paper presents the hardware construction and working schematic of the manipulation system. Before crack sealing, a supervised method based on deep learning is used to detect the cracks and obtain the cracks' image information, which can be merged with depth information to acquire the accurate location information of cracks. We validate the feasibility of the crack sealing end-effector which can be applied to seal cracks on uneven road surface by indoor simulation tests.**

I. INTRODUCTION

Each year, millions of dollars are invested on road maintenance and reparation all over the world [1]. One of the most common methods of road pavement preventive maintenance is crack sealing. Because effective crack sealing can help to prevent water and debris from penetrating the road pavement [2] so that it can ensure roadway structural integrity and extend the time between major rehabilitation. Conventional crack sealing operations exposes workers to dangerous conditions like as bad weather and speeding vehicles and can be tedious, and so on. In addition, a typical sealing operation by workers is time consuming and inefficient. Since automatic crack detection and sealing systems are safer, lower costing, more efficient, and more objective, so using automatic crack detection and sealing systems to replace the existing manual methods will be an development trend. The research about them has attracted wide attention from both the academy and the industry [3],[4],[5],[6].

Recently, more and more researchers have developed deep convolutional neural networks (CNN) for automated crack detection for road pavement. Zhang et al. [4] proposed an automatic road crack detection method based on deep CNN trained to classify $99 \times 99 \times 3$ image patches acquired by a low-cost smart phone sensor. Pauly et al. [7] created $99 \times 99 \times 3$ image classifiers to demonstrate the effectiveness of using deeper CNN in improving the accuracy of pavement crack detection. Cha et al. [8] proposed a damage detection method based on the faster region-based CNN (Faster R-CNN). Dung and Anh [9] proposed a crack detection method based on deep fully convolutional network (FCN) for semantic segmentation on concrete crack images. For road pavement maintenance, it is an important task to detect the crack before crack sealing operation. In this paper, we use the method [10] that we have proposed for road pavement crack detection to obtain the crack 2D map. The method is also based on deep CNN.

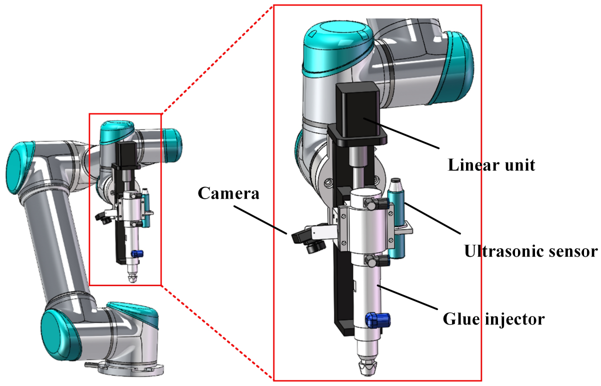

Fig. 1. The mechanism design of the crack sealing end-effector.

Traditional crack sealing is a labor intensive and hazardous process. Therefore, many efforts have been made to automate the process of crack sealing. Kim et al. [11] proposed that complete automation of crack sealing operations is not feasible, it should find a desirable balance between human and machine functions. Zhang [12] proposed a unified crack and sealed crack detection approach that can detect and separate both cracks and sealed cracks under the same framework. In this paper and Ref. [13] transfer learning has been proved to improve the efficiency and accuracy of a crack classifier.

Most of the previous studies have proposed methods based on image classification and/or object detection using deep learning. For crack detection systems, many devices like autonomous robotic systems that are used for bridge deck inspection [14],[15], crack detection in civil structures [16], and steel crack detection [17], have been developed. However, the survey found that there are almost no robotic systems for automatic crack sealing.

So in this paper, we mainly design and implement a manipulator system for roadway crack sealing. In particular, a

*Corresponding Author: Zhun Fan is a Full Professor with the School of Electrical and Information Engineering, Shantou University, Shantou 515063, China. Email: zfan@stu.edu.cn

All authors are with Key Lab of Digital Signal and Image Processing of Guangdong Province, College of Engineering, Shantou University, Shantou 515063, China. http://imagelab.stu.edu.cn/

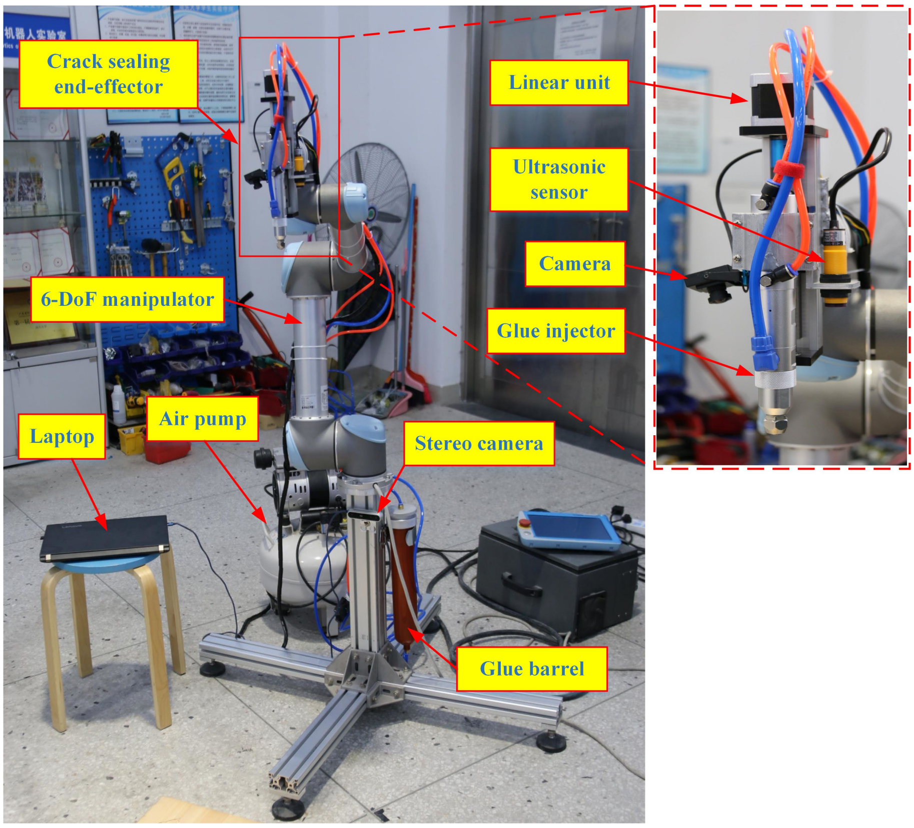

Fig. 2. The physical diagram of the proposed manipulator system.

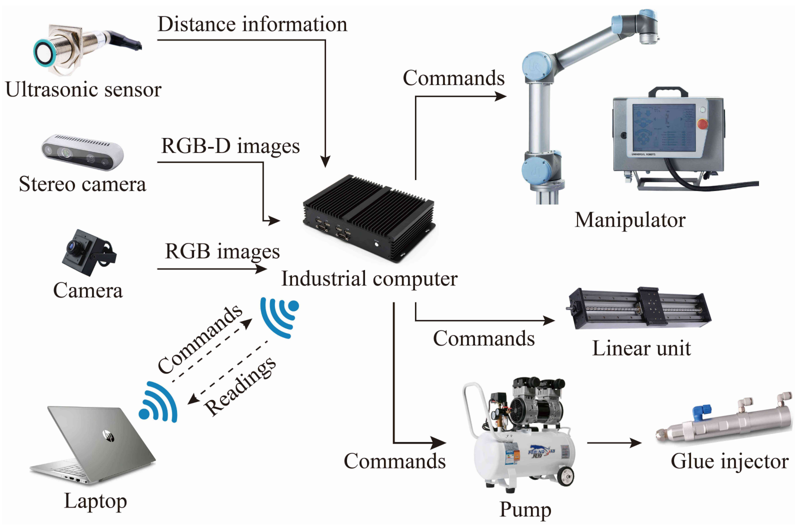

Fig. 3. The connection of the subsystems.

novel crack sealing end-effector is shown in Fig. 1, which is a crucial component of the proposed system, is presented and used for sealing cracks on uneven road surface. The remainder of this paper is organized as follows. In Section II, we describe the manipulator system for roadway crack sealing. Section III presents the experimental plans and methods for testing the feasibility of the crack sealing end-effector and the manipulator system. The experimental results are presented and analyzed in Section IV before the conclusive summary is presented in Section V.

II. MANIPULATOR SYSTEM

This section presents an overview of the manipulator system. As shown in Fig. 2, the hardware setup of the manipulator system consists of:

- one six-degree-of-freedom(6-DoF) manipulator;
- one crack sealing end-effector;
- one stereo camera;
- one air pump;
- one glue barrel;
- one laptop.

In Fig. 3, we show the connection relationship between subsystems of the manipulator system, where an industrial grade computer is incorporated in the manipulator system, which allows to be accessed and remote controlled by a laptop through a wireless network. In this system, the industrial computer is not essential, we can directly use the laptop instead of the industrial computer to receive information (e. g., distance information from ultrasonic sensor, crack RGB-D images from stereo camera, RGB images after crack sealing from camera.) and issue control commands (e. g., manipulator motion commands, linear unit motion commands, and pressure adjustment commands.).

For complex manipulation task, a light-weight, high-payload 6-DoF manipulator (from Universal Robots Inc.), is mounted on the manipulator base. The maximal reach of the manipulator is 850cm and the maximal payload is 5kg. The end of the manipulator is repeatedly positioned with an accuracy of 0.1mm.

The crack sealing end-effector is attached on the end of the manipulator, as a key part of the manipulator system, which consists of a linear unit, an ultrasonic sensor, a glue injector and a camera. The linear unit is a linear actuator, which is mounted on the end of the manipulator. Here the transmission mode of the linear unit is assisted by a ball screw and a linear guide. The ultrasonic sensor and camera are mounted on both sides of the glue injector. They are all driven up and down the screw by a motor at the top of the linear unit. The ultrasonic sensor is used to measure the distance between the glue injector and the cracks on the road pavement. It has a measurement range of 60-1000 mm, a distance resolution of 0.5mm. The injection height, which is a vertical distance from the nozzle of the glue injector to the cracks, is an important parameter for crack sealing. With the linear unit, the injector height can be adjusted according to the distance information from the ultrasonic sensor in the process of crack sealing. In addition, the camera is a normal RGB camera with a resolution of 800×600 and a monitoring distance of 0-5m, which is used to observe the glue injection status and the crack sealing effect.

Crack detection is an important step before crack sealing. In order to collect images of cracks in the work area for calculating the position of the cracks that can be sealed, we mount the stereo camera on the manipulator base. The camera is an Intel RealSense D415 RGB-D camera with a resolution of 1280×720 and a field of view of $69.4° \times 42.5° \times 77°$. This camera is suitable for crack image information acquisition in indoor and outdoor.

To successfully seal the cracks in the roadway surface, high-strength roadway sealant is injected to fill the cracks. The sealant is stored in the glue barrel attached to the manipulator base and is squeezed to the glue injector from the barrel through the air pump.

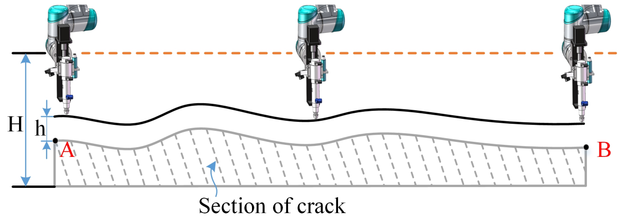

Fig. 4. The experimental schematic for testing the feasibility of the crack sealing end-effector.

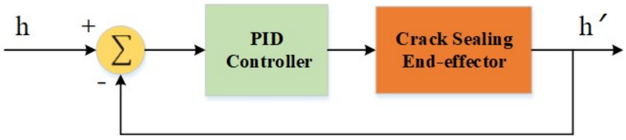

Fig. 5. Control diagram of the injection height based ultrasonic ranging.

III. EXPERIMENTAL PLANS AND METHODS

In order to verify the feasibility of the crack sealing end-effector we designed , here we have designed a experiment. In Fig. 4, we show the experimental schematic for testing the height adjustment ability of the crack sealing end-effector that the height of the glue injector can vary with the uneven road surface. Where the dotted line indicates the section of roadway crack, h is the injection height and H is the height of the end of the manipulator from the horizontal road surface. In our experiment, we set H and h to be a fixed value and ensure that the end of the manipulator moves along the crack growth direction($A \rightarrow B$). During the manipulator moves from A to B, the ultrasonic sensor will measure the distance from the glue injector to the road surface, and the height of the glue injector from the road surface should remain unchanged through the adjustment of the linear unit.

The crack sealing end-effector control diagram is shown in Fig. 5. Where h as an input is the expected value of the injector height; $h^{'}$ as an output is the actual value of the injector height, and the crack sealing end-effector is controlled continuously by using a PID controller. In our experiment, we will simulate an uneven road crack with

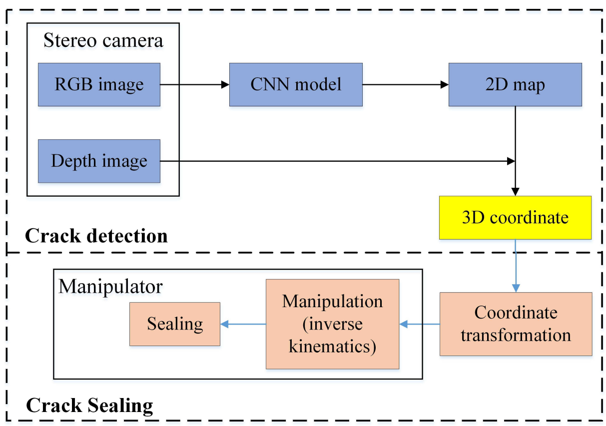

Fig. 6. The overview of the manipulator system for crack detection and crack sealing.

a length of 45cm, and in order to accurately measure the actual height of the glue injector to the road surface, we will use the Optitrack motion-capture system to obtain the motion data of the glue injector and calculate the actual height $h^{'}$ with the motion data.

Crack detection is a significant and essential step before crack sealing, so we should detect the cracks and know their exact location within the working range of the manipulator system. In this context, we use the method [10] that we have proposed before to accomplish the crack detection. Following the idea developed by the Advanced Highway Maintenance and Construction Technology Research Center [18], we mainly detect random cracks(transverse and diagonal cracks) and longitudinal cracks. In this paper, we use supervised method based on deep learning instead of traditional image processing method. More precisely, our method based on structured prediction with the CNN. A batch of labeled data were provided to the proposed CNN model for training as a training set. After the training is completed, RGB images provided by the stereo camera were input into the model and the bounding box of the cracks can be obtained, which means the 2D map of the cracks can be obtained. In addition, the 3D coordinate of the cracks in the camera coordinate system can be obtained by merging the 2D map and the cracks' depth information. After coordinate transformation and inverse kinematics solution, the manipulator system can accomplish the crack sealing task. The overview of the manipulator system is shown in Fig. 6.

IV. EXPERIMENTAL RESULTS

In this paper, in order to evaluate the performance of the manipulation system, we first tested the crack sealing end-effector through an indoor simulation experiment. The experimental result is shown in Fig. 7. where the red line (from A to B) indicates an uneven road surface and the black line indicates the height curve of the nozzle of the glue injector (i.e., the actual height $h^{'}$ in Fig. 5.), which varies with the height of the ground and remains approximately 1.5cm (h = 1.5cm) above the ground. Here we set Aa and Dd has the same height of o.8cm and EF has a height of 2cm. By comparing and analyzing the two lines, we find that the end-effector can be applied to the uneven roadway. It means that the end-effector is feasible for sealing cracks on uneven roadway. The main reason is that when the ultrasonic sensor detects that the injection height is greater or less than the set height h, the linear unit will drive the glue injector to move downward or upward until the injector height detected by the ultrasonic sensor arrive at stable height h. In addition, since the motion of the linear unit is a linear motion process, the changing of injector height at point C, E, F, D and B is a continuous gradual process, and there is a motion lag due to inertia at these points.

For the manipulator system we proposed, crack detection is an indispensable step. Usually, we need to know where the cracks are and which pixels belong to the crack pixels

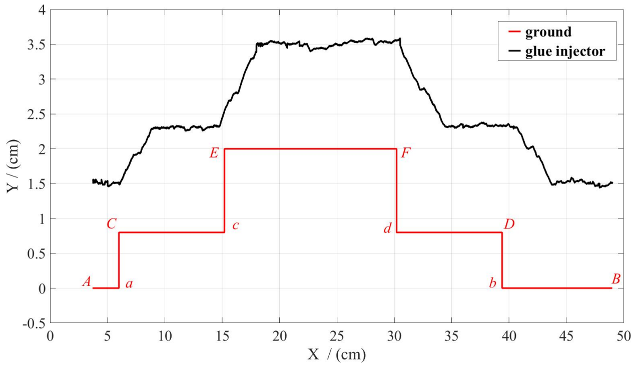

Fig. 7. Experimental results of the glue injector height changes with roadway surface.

in the image which the stereo camera captured. According to the operation flow chart shown in Fig. 6, we use a supervised method [10] based on CNN that we proposed to detect cracks in the images. The proposed method is trained and tested on a database CFD [19] with RGB images. Exemplar detections on CFD are shown in Fig. 8. The output of the network is a probability map as shown on the last row. According to the output images in Fig. 8, the method we used can detect the cracks and effectively deal with the cracks with complex background and complex topologies. More experimental results for verifying the effectiveness of the method can be found in Ref. [10], we therefore shall not elaborate further here.

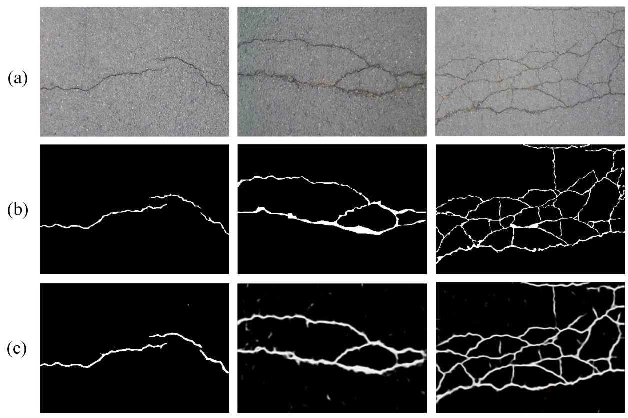

Fig. 8. Part of crack detection results by the proposed method. (a) original images; (b) ground truth; (c) probability maps.

In order to evaluate the performance of the manipulation system, we will use the method proposed in Ref. [10] to detect the cracks within the working range of the 6-DoF manipulator. The experimental setup is shown in Fig. 9. For transverse cracks, we seal the cracks from left to right along the crack growth direction. For longitudinal cracks, we start the crack sealing from the far end along the crack growth direction. To further verify the feasibility and effectiveness of the proposed manipulator system, more experiments should be conducted in indoor and outdoor environment and they are in the list of our future work.

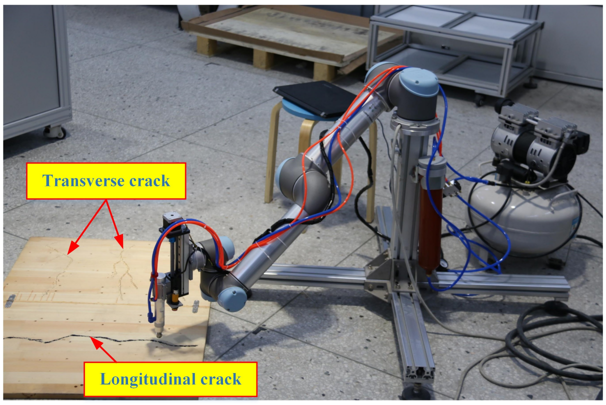

Fig. 9. The experimental setup in the lab for transverse and longitudinal cracks sealing using the proposed manipulator system.

V. CONCLUSION

Crack sealing is a very important procedure used to extend the life of road surface. In this paper, we presented a manipulator system for roadway crack sealing. The manipulator system consists of a six-degree-of-freedom manipulator, a crack sealing end-effector which attached on the end of the manipulator, a stereo camera mounted on the base of the manipulator, a glue barrel, an air pump and a laptop. We also introduced the crack sealing end-effector in detail. The end-effector can flexibly adjust the glue injection height from the glue injector to the crack according to the distance information from the ultrasonic sensor, thereby making the manipulator system more suitable for sealing the cracks on uneven road surface. Finally, we demonstrated the feasibility of the crack sealing end-effector and the overall system with indoor tests. Since the six-degree-of-free manipulator in the proposed manipulator system is fixed on the base, the system can only seal the cracks in the working rang of the six-degree-of-free manipulator. In the future, we will port the manipulator system to a wheeled mobile platform and conduct algorithm research related on crack detection and sealing, especially for actual roadway cracks.

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