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Crack Inspection Support System for Concrete Structures Using Head Mounted Display in Mixed Reality Space

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Abstract: The number of concrete structures that are more than 50 years old is increasing. Since these concrete structures must be inspected periodically, automatic crack inspection methods are utilized, such as image processing to find shapes of cracks on the concrete surface. The crack inspection result needs to be corrected and confirmed off-line by an operator to verify that there are no missed defects or false positives. In this paper, we developed a crack inspection support system using a head-mounted display (HMD). The proposed system consists of building 3D models by spatial sensing, detecting and matching features of cracks from captured images, and finally superimposing and projecting detected cracks onto the real structure surface in a mixed reality (MR) space. Through experiments, we confirmed that the proposed system could acquire 3D data of concrete structures that can be measured easily in real time and onsite. In addition, it is possible for the operator to confirm the crack measurement analysis by comparing measured results with the actual structure in the MR environment. Thus, the proposed system unifies the previously separated processes of 3D data creation and analysis used in concrete structure inspection.

Keywords: Mixed Reality, Head Mounted Display, Crack Inspection, Image Measurement.

1. INTRODUCTION

Many of the concrete structures in Japan were built after a period of high economic growth, and the number of concrete structures over 50 years old is increasing [1]. As infrastructure ages, there is a critical problem in that the time required to maintain the concrete structures increases. In particular, cracks occur on the concrete surface in the initial deterioration stages of the concrete structure [2]. The cause of the crack is estimated by analyzing the width, position, and shape of the crack. Then, it is determined whether or not the concrete must be repaired. Therefore, it is important to detect the position, width and length of cracks with high accuracy for proper maintenance of concrete structures.

In order to perform crack inspection of concrete structures efficiently, a number of studies on automatic crack detection though computer-based imaging have been conducted [3-6]. The methods demonstrated have shown a certain effectiveness supporting image-based crack inspection, and the applications have already been developed for this purpose. However, because the detection results are not accurate enough, it is necessary for a trained operator to confirm the results by comparing the automatic inspection result with the actual structure in order to make a final judgment on the inspection results. Therefore, even if automatic inspection technology is developed, it is necessary for a human to intervene in the inspection.

On the other hand, recent developments of virtual reality and augmented reality have opened the door to using head-mounted display (HMD) as the user interface technology. Much research has been conducted thus far on applications using HMDs [7-9].

In the field of the civil engineering, there are systems that use mixed reality (MR) to arrange 3D data of structures, such as from computer-aided design (CAD) and building information modeling (BIM) software, onto a virtual space. Inspection results, including 3D data and structure information, are then presented on the virtual space for inspectors [10, 11]. These systems are also expected to be effective in the inspection of concrete structures, however, it is necessary to create 3D data by hand if there is no existing 3D data of the structure. In addition, even when 3D data exists, it is difficult to superimpose the inspected results onto the 3D data because this must be done manually.

Thus, it is often noted that information processing technology in structure inspection can improve automation and efficiency, but human involvement is necessary to make up for incomplete inspection data and missing 3D structure data. Therefore, in this study, we construct a new cyber-physical framework that effectively connects digital data from a cyber space with human work in the physical space.

In this paper, we develop a system that creates 3D data in real-time on the concrete surface and presents the results of crack inspection to workers simultaneously via HMD. In the proposed method, 3D data is created by using a depth sensor. Cracks are then detected by capturing a high resolution image of the concrete and matching the image features to a low resolution image from the HMD. The result is then presented to the worker in a MR space.

2. THE PROPOSED METHOD

In this section, we describe a system to support the whole process of crack inspection on the practical site. The proposed method uses a HMD with depth sensor and a high-resolution camera. The first step in the

† Tomoyuki Yamaguchi is the presenter of this paper.

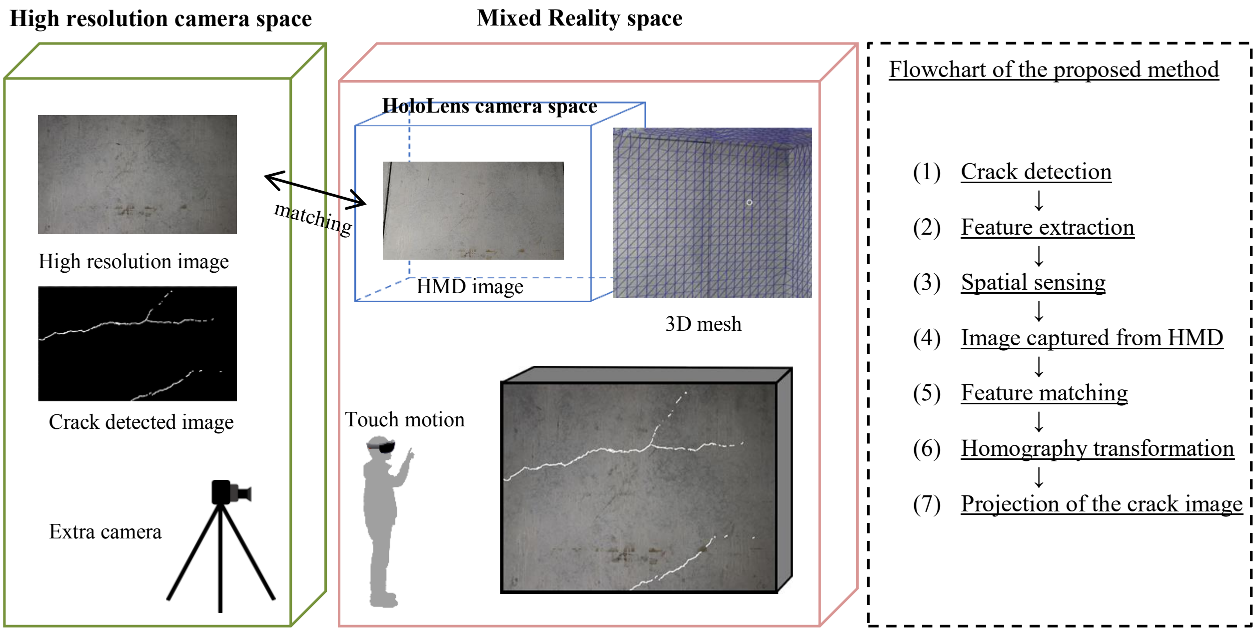


Fig.1 Overview of the proposed system

proposed method is capturing the concrete surface with a high resolution camera. Image-based crack detection is performed on these captured images using the crack detection system [4]. Then, 3D data of the concrete structure is created by the HMD via a depth sensor. Image matching is performed between previously captured high resolution images and low resolution images taken with a camera on the HMD. The crack detection image is projected to the matched position from the HMD on the MR space. By displaying on the MR space, the user wearing the HMD will observe that the detection result is directly displayed on the concrete surface in the real space. In this way, the proposed method realizes real-time crack inspection support at the practical site.

Figure 1 shows an overview of the proposed method. This method consists of 7 steps, and the details of each step are described below.

(1) Crack detection by high resolution images

At first, the concrete surfaces are captured with a high resolution camera to measure cracks accurately. In fact, it is necessary to measure the cracks at a width of 0.2 mm. In order to detect cracks by image processing, a resolution of 0.05 mm/pixel is required. For image-based crack detection, we employ the crack detection system [4]. The crack detection image and original image are stored as a set in a database.

(2) Feature extraction from high resolution images

Since feature matching between high resolution camera image and images from the HMD is performed in step 5, feature extraction from the high resolution image is performed in this step. In addition, high resolution images are different from HMD images in size, so feature extraction is performed after resizing to the HMD image sizes. The characteristics of the feature used for feature extraction are described in Sec. 3.2.

(3) Spatial sensing

In order to obtain 3D data of the concrete structure, depth information is acquired by a depth sensor built into the HMD. Next, simultaneous localization and mapping (SLAM) is performed using an internal acceleration sensor on the HMD to build 3D information. Here, the created 3D data is represented as a 3D mesh which is constructed from detected vertices, edges, and faces. These spatial sensing tasks can be performed by the operator wearing the HMD and looking around the target concrete structure.

(4) Image captured from HMD

The operator specifies the area to view the inspection results and acquires the image from the HMD camera. Next, the crack detection image stored in the database is projected onto the specified MR space coordinates. The users can take pictures interactively by via touch motion in MR space.

(5) Feature matching

Feature extraction of the images from the HMD camera described in step (4) is performed. Next, matching processing is performed between the extracted features of the HMD images and the image features in the database extracted in step (2), and an appropriate image is selected. The matching method employs a Brute-Force matcher approach in this study. Brute-Force matcher is simple approach which takes the descriptor of one feature in the first set (high resolution images) and is matched with all other features in second set

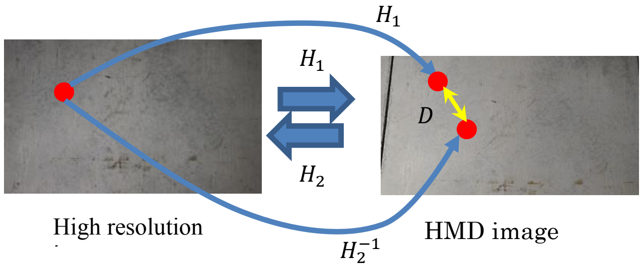


Fig.2 Calculation process for matching

(HMD images) using some distance calculation.

(6) Homography transformation

The homography matrix is estimated using the matching result with the high-resolution camera image determined to be compatible with the HMD camera image. The matching result contains some outliers that were misjudged. Therefore, in our method, the homography matrix is estimated using RANSAC[12], which is known as a robust estimation method that is not susceptible to outliers. Finally, the high-resolution image can be transformed by using the obtained homography matrix.

(7) Projection of the crack image

Since the geometrical relationship between the HMD camera image and the high-resolution image is calculated, the position of the projected image on the 3D mesh is also calculated and represented to the user.

3. THE DEVELOPED SYSTEM

3.1 Mixed Reality Head-Mounted Display

The system needs and required specifications include a depth sensor for spatial sensing, RGB camera for capturing a concrete wall image, holographic display for presenting 3D data, and processing capability for feature matching and homography transformation in real-time. In this study, we utilized a Microsoft HoloLens [13]. HoloLens is capable of spatial sensing with a distance sensor and infrared sensor and includes a built-in RGB camera with 2.4 mega pixel resolution, CPU, and GPU.

In addition, as a high-resolution camera, we used CANON EOS70D (20 mega pixels) to measure cracks accurately.

3.2 Feature detector/descriptor for concrete images

We employ OpenCvSharp-UWP for developing the system [14]. Here, accuracy and speed are evaluated using ORB, BRISK, KAZE and AKAZE as feature detectors/descriptors [15], which are supported by OpenCvSharp-UWP in order to determine the suitable method for applying concrete images.

As specific procedures, the homography matrix H_1 is calculated by performing feature matching with a crack image taken by a high-resolution camera as in the first set; $\mathbf{x}$ and concrete images taken with HoloLens as in the second set; $\mathbf{x}'$ as shown in Eq.(1).

(a) High resolution image (Image 1 with cracks)

(b) HMD image

Fig.3 Images for the evaluation of feature detector

Table 1 Results for the evaluation of accuracy (pixel).

Image no.	ORB	BRISK	KAZE	AKAZE
1 (crack)	778.78	4.06	2.30	2.33
2 (crack)	2357.26	220.47	2.19	2.87
3 (crack)	323.88	2.33	1.36	1.08
4 (no)	1017.60	320.84	21.14	16.25
5 (no)	104.97	1.44	1.58	1.50
Average	916.50	109.83	5.72	4.72

Table 2 Results for the evaluation of the cost (sec.).

	ORB	BRISK	KAZE	AKAZE
Average	0.66	2.99	32.96	4.81

$$\mathbf{x}' = H_1\mathbf{x} \tag{1}$$

Next, the first set and the second set are reversed to calculate the homography matrix H_2. Coordinate transformation of the high-resolution camera image is performed using H_1 and the inverse matrix of H_2, respectively.

$$\mathbf{x}'' = H_2^{-1}\mathbf{x} \tag{2}$$

Finally, the distance error D is calculated from whole pixels of the image and represented in the following equation.

$$D = \text{average}\left\{\sqrt{(\mathbf{x}'' - \mathbf{x}')^2}\right\} \tag{3}$$

The matching calculation processes are figured in Fig.2.

In the evaluation for the selection of a suitable feature descriptor, the high-resolution camera images used are a total of 5 images: 3 images with cracks and 2 images without cracks. Also, the HoloLens camera captures 10 images for each crack image, for a total of 50 images. Fig.3 shows the examples of the images. The results are shown in Table 1. In addition, Table 2 shows the results of the average calculation cost for feature matching in seconds. In this evaluation of the calculation cost, we used 3 images (high resolution) with cracks and 10 images (HMD images) for each crack image.

From Table 1, it can be seen that AKAZE is very accurate and equal to, or better than KAZE. On the other hand, from Table 2, KAZE has the highest detection time. The detector with the fastest time is ORB, then BRISK and AKAZE. From these results, it was confirmed that AKAZE with high accuracy and a certain speed is suitable for concrete walls in this system.

4. EXPERIMENTS

4.1 Experimental setup

The experiment is conducted using the specimen concrete structure installed in the indoor room. The size of the concrete structure is 168 cm high, 150 cm wide, and 243 cm long as shown in Fig. 4. Fig. 5 shows the photograph of the concrete structure. The experimental area is the rectangular area surrounded a green border. The actual crack locations are indicated by red lines in Fig. 6.

In advance, we prepared the high-resolution images and crack detected images from the step (1) in Fig. 1. For the rectangle area of Fig. 6, there are total of 9 concrete wall images; including 3 crack images and 6 non-crack images, and the corresponding crack detection images created from them are registered in the database. Finally, Fig. 7 shows the experimental situation.

4.2 System operation experiment

In order to confirm the operation of the developed system, verification of the image projection in MR space is performed on the concrete structure.

Fig.8 shows the results of 3D meshes created by the examiner. By moving the point of view on the concrete surface, it can be confirmed that 3D meshes were generated. Fig.9 shows how crack detection images are projected to the operator by the proposed system based on the procedure of Sec.2 and using AKAZE as the feature descriptor verified in Sec.3. The black colored areas are the range where the matched images are projected. The white colored lines are projected as detected cracks in the crack detection image. Here, since black color is transparent in HoloLens and, only white lines of cracks can actually be seen for the operator as shown in Fig.10. The image was not projected at the red dotted circle in Fig.9. The reason is considered to be that the image matching failed because the specular reflection by the illumination was strong on the concrete surface. In addition, at the red dotted rectangle in Fig.9, the image was not projected correctly on the 3D mesh. If the mesh was uneven and was not expressed in a plane, it is considered that the image pasting failed.

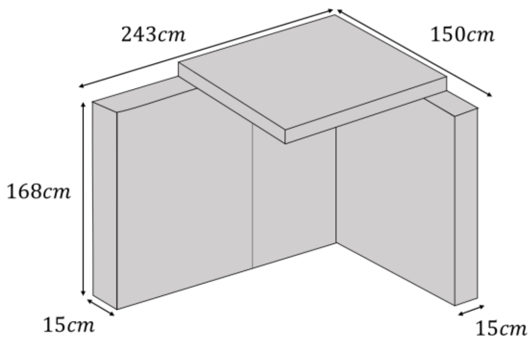


Fig.4 The design of the specimen concrete


Fig.5 The concrete walls for experiment


Fig.6 The experimental rectangle area and cracks of the correct answer

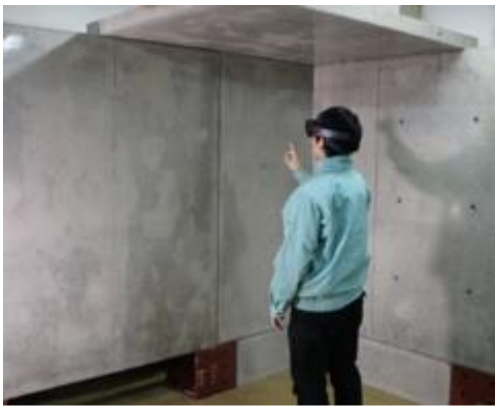
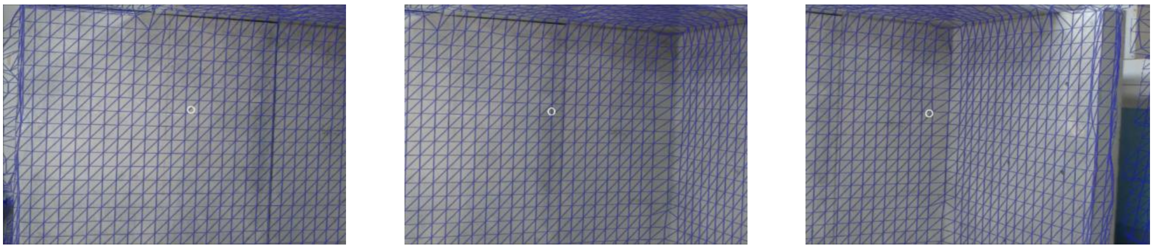


Fig.7 Experimental situation



(a) left direction (b) middle direction (c) right direction

Fig.8 Spatial sensing to create 3D meshes (whited circle represents viewpoint)

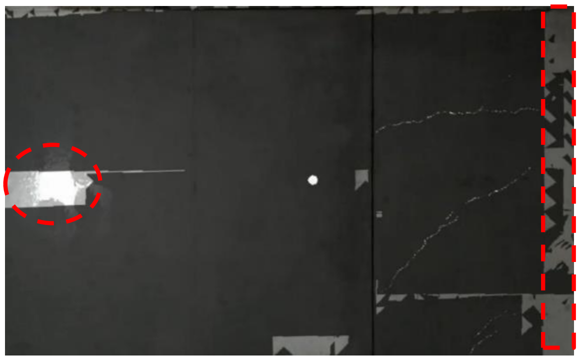


Fig.9 Whole results of the projected images

Fig.10 The user's point of view (cracked area)

width[mm]
0.06~0.10
0.10~0.15
0.15~0.30
0.30~0.50
0.50~0.60
0.60~1.00

Fig.11 Crack width measurement with color code

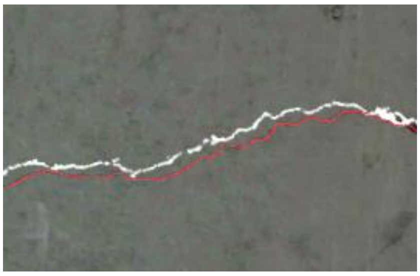


Fig.12 Comparison with correct crack (red color)

Therefore, the setting of the lighting condition and the creation process of the 3D mesh are improved in the future.

An enlarged image of the cracked area is shown in Fig. 12. In Fig. 12, the red color line represents the correct cracks. It is observed that some errors in position occur between the projected crack and the correct crack. This is considered to be because the error in spatial sensing which affects the projected position of the crack. This problem is discussed in section 4.3. Moreover, Fig. 11 shows a projected image in which the crack width of the crack detection image can be identified with different colors using our crack measurement method [3]. This experiment shows that the crack width could be represented by different colors. The proposed system could show not only the crack positions and also crack width.

4.3 Evaluation of the spatial sensing

Accuracy of the spatial sensing is important when the images are projected to the user in MR space. In this paper, we verified accuracy of the spatial sensing on a concrete structure by the proposed system.

We measured the position error of the 3D mesh as the wall of the structure created by the proposed system and the correct position as ground truth. In order to investigate the influence of lighting intensity, this experiment was performed by changing external lighting conditions, and measuring illuminance. The measurement positions are six different points on the wall shown in Fig. 13. The vertical distance between the 3D mesh and the actual wall was measured. Tables 3 and 4 show the results when the lighting condition is brighter and darker.

From the results, the average error was 4.7 cm for brighter illumination and 3.3 cm for darker illumination. This is because the measurement error of the infrared sensor on the HoloLens increases with higher illuminance. Therefore, it is necessary to pay attention to the specular reflection on the concrete surface when using external lighting.

5. CONCLUSIONS

In this paper, we proposed a novel system that could support inspectors during crack inspection in the field. The procedure of our system consists of 7 steps, and the

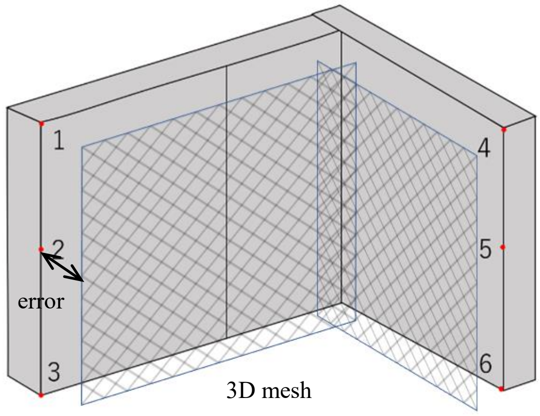


Fig.13 Evaluation manner of the errors

Table 3 Results in brighter environment

	No.1	No.2	No.3	No.4	No.5	No.6
Error[cm]	8.0	4.1	5.5	4.9	2.8	3.0
Illuminance [lx]	224	168	188	914	309	188

Table 4 Results in darker environment

	No.1	No.2	No.3	No.4	No.5	No.6
Error[cm]	3.3	3.5	4.5	2.9	2.1	3.4
Illuminance [lx]	63	88	94	84	126	91

system needs only of a HMD and a high-resolution camera.

Through experimentation, we confirmed the proposed system could measure 3D data from a concrete structure when in turn can be measured easily in real-time and on-site. Moreover, while the crack inspection result needs to be corrected and confirmed off-line, it is possible for the operator to confirm the crack measurement results analyzed while viewing the actual structure in the MR space. Thus, the proposed system unifies the previously separated processes of 3D data creation and analysis. In the experiment of spatial sensing accuracy, an average error of 4.7 cm in a brighter environment, and an average error of 3.3 cm in a darker environment were recorded. The error observed in crack projection is caused by the influence of measurement error that occurs in spatial sensing. As a result, it was confirmed that the accuracy of the projection could be improved if the system was operated with less external light.

In the future, we are planning to conduct experiments to see if this system can be applied to different structures. Moreover, since a camera that can capture cracks with high accuracy can be implemented in the proposed system, we will apply images by drone camera to our system in future experiments.

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