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Rapid geometrical inspection system for precast bridge slabs using laser scanning

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ABSTRACT

This study presents a new technique that enables entire surface geometric quality inspection (GQI) of prefabricated bridge slabs without a registration of point cloud data. The current multiple scans and registration approach for the GQI of planar-type construction elements are time consuming and error prone due to registration errors. This study aims to develop a rapid and accurate registration-free data acquisition technique for the GQI of PC slabs. To do this, a scan planning method using flat mirrors is proposed. For validation, a series of simulation and experimental tests are conducted to investigate the performance of the proposed method compared to the traditional registration-based method. The results show that the proposed technique is more efficient and feasible over the current GQI approach, demonstrating its applicability in real applications during the manufacturing and construction stages.

1. INTRODUCTION

Over the past decades, precast concrete panels such as precast walls, beams and columns have gained popularity due to the rising urbanization and construction activities [1]. Compared to the in-suit concrete casting panels, precast concrete (PC) elements offer reduced construction time and more consistent properties, making the construction process more efficient and economical [2]. Despite the high demand and all these benefits, PC elements with unacceptable deviations exceeding specific tolerances may adversely affect both aesthetic and functional performances of the structure [3]. Therefore, it is necessary to check the dimensional and quality property of the PC

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elements to ensure its conformity with the as-designed model at the manufacturing stage. Recently, 3D laser scanning has been widely used and considered as a promising 3D data acquisition technology for geometric quality inspection (GQI) PC elements because of the nature of non-contact and accurate measurement [4].

The authors' research group has proposed several GOI techniques for PC elements using laser scanning. Kim et al. developed an edge extraction algorithm [5] and proposed an end-to-end framework that integrate the laser scanning technique with building information modeling (BIM) for GQI of PC elements [6]. Afterwards, the developed GQI approaches were further improved and validated on full-scale PC elements with complex geometries through field tests [7]. In addition, an automated GQI technique was developed for the GQI of the side surfaces of PC elements having complex structural features such as shear keys and flat ducts on the side surfaces [8]. Recently, the research group proposed a mirror-aided scanning system that can scan the side surfaces of PC elements even to address the scan of invisibles from the laser scanner [9], resulting in registration-free data acquisition without changing the laser scanner locations.

However, the scope of the precious proposed techniques is mostly limited to small-scale components. As for large-scale construction components, registration of multiple scans at different scanning positions are inevitable, which is time-consuming and registration-error prone. To address the limitation, this study aims to propose a mirror-aided system for accurate and rapid GQI of prefabricated bridge slabs. The proposed technique uses flat mirrors in order to scan invisible surfaces of a prefabricated bridge slab from a laser scanner and thus allow for the entire surface GQI of the target component. The originalities in this study compared to the previous work include 1) development of a mirror-aided system for GQI of prefabricated bridge slabs, 2) a new scan planning method is developed to determine the optimal locations of the laser scanner and flat mirrors. Finally, the proposed method is then validated through numerical simulations and experiments on a full-scale prefabricated bridge slab.

2. OVERALL SCHEME OF MIRROR-AIDED TECHNIQUE

Figure 1 shows the proposed mirror-aided GQI of prefabricated bridge components. Note that the geometric inspection is conducted in an indoor environment before being delivered to the construction site, meaning it is reasonable to locate the laser scanner locations above the prefabricated bridge components. Here, two laser scanner locations are set above the prefabricated bridge component with the support of the frame, which aims to address the effects of the long scanning distance and high incident angles. The laser scanner is first located at the laser scanner location I for the first scan and then slips along the frame to the laser scanner location II for a second scan, resulting in a complete scan of top surface of the prefabricated bridge component. Moreover, plane mirrors are situated along the four side surfaces so that the laser beams can reach the side surfaces through the mirrors. There are also rectangular patches attached on the surfaces of flat mirrors to obtain scan points falling onto the patches. When the laser scanner slips from location I to location II, the two mirrors located at Mirror

I and Mirror II that are set along the longitudinal side surface also slip along the frame to Mirror III and Mirror V for the next scan. In this way, both the top and side surfaces, which are outside of the scanning view of the laser scanner, can be scanned at the same scan, which reduces scanning time and results in an efficient geometric inspection.

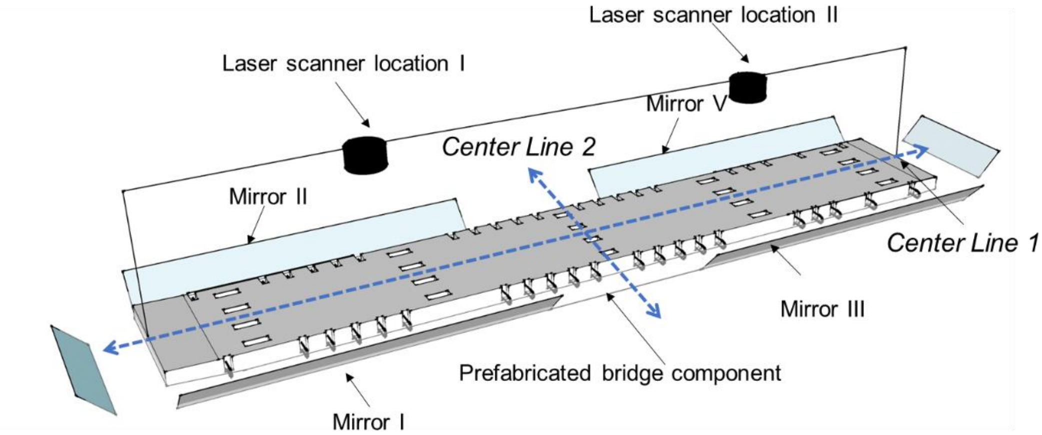

Fig. 1 The proposed mirror-aided GQI of prefabricated bridge components

3. DETERMINATION OF SCAN CONFIGURATION

This step aims to determine the optimal laser scanner locations and mirror locations based on the boundary extraction accuracy and scanning time for top surface of the prefabricated bridge component. There are four steps for laser scanner location determination, which are 1) generation of potential laser scanner locations, 2) estimation of boundary line extraction accuracy, 3) estimation of scanning time and 4) determination of optimal laser scanner location.

First, potential laser scanner locations are generated above the prefabricated bridge slabs. Note that the two laser scanner locations are created along Center Line 1 and symmetric with each other along the Center Line 2 as shown in Figure 2. Then, scan points are simulated on the top surface of the prefabricated bridge slabs with respect to each generated potential laser scanner location for boundary line extraction. Next, the scanning time for each potential laser scanner is estimated based on the horizontal scan coverage and angular resolutions. After estimating the boundary line extraction accuracy and scanning time, a performance metric $E(k)$ is formulated to qualify the potential laser scanner location based on indicators of boundary line extraction accuracy $Acc(k)$ and scanning time $T(k)$. Here, W_a and W_t are the weight of the edge line detection estimation accuracy $Acc(k)$ and scanning time $T(k)$ and the sum of W_a and W_t is 1. Note that the weight can be selected according to the demand of the project. Finally, the optimal laser scanner location is determined as the potential laser scanner location with the highest $E(k)$. After determining the laser scanner location, the mirror positions are located to enable the full scan of the side surface with respect to the determined laser scanner locations based on the mirror reflection principle.

4. VALIDATIONS

The effectiveness of the scan configuration determination method was first verified by generating numerous candidates for the determination of laser scanner position. Figure 2 shows a set of 2D grid with a resolution of 1 m (length) ×1 m (height), which was created in an area of (5 m (length) × 2 m (height)) above the PC slab, resulting in the generation of 18 potential positions for laser scanner I. Note that the corresponding laser scanner II is generated based on the symmetric relationship with the laser scanner I. Among those locations, three positions were selected for the model validation to compare the simulated scan points with the collected scan points. Here, those three locations, $P_{i,_{i=1...3}}$, were selected as those locations. Those locations have different performance metric $E(k)$ with locations of (P_1 (0m, 1m, 4m)), (P_2 (1m, 1m, 4m)) and (P_3 (3m, 1m, 4m)) as presented in Figure 2. Note that weight (E_a) given to boundary extraction accuracy (Acc) is set as 0.8 while weight (E_t) of 0.2 is given to scanning time (T). After determining the laser scanner location, the mirror locations are generated along the side surface based on the mirror reflection principle to cover the full side surfaces. which has a distance of 0.45 m from the side surface of PC slab with vertical angle of 60°.

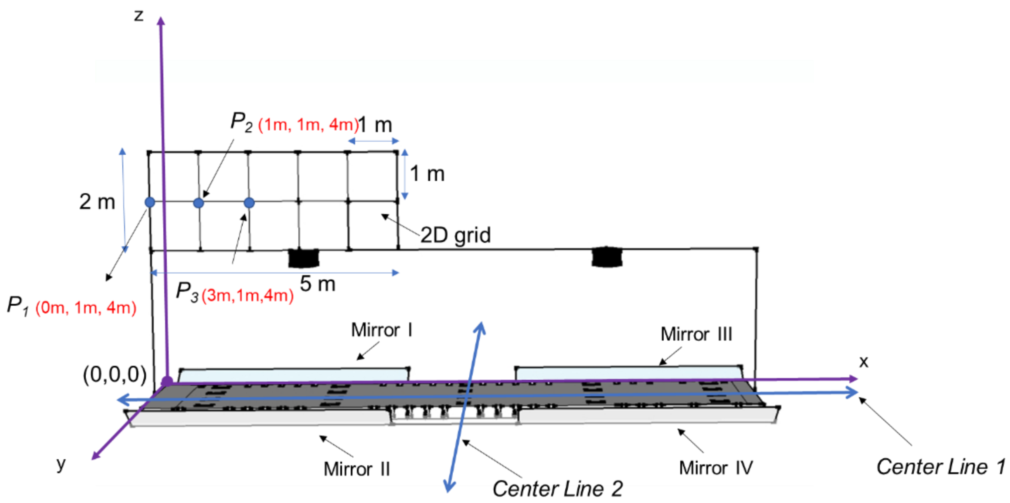

Fig.2 Generation of position candidates and selected three laser scanner locations used for validating the geometrical relationship model

To validate the effectiveness of the scan planning method, experimental validations are conducted according to the determined scan configurations for comparison with the simulated results. Table 1 shows the comparison of edge line accuracy on PC slabs and scanning time simulation results at the generated laser scanner locations. Overall, a 76.1% and 78.9% average similarity between the simulation and the experiment for edge line estimation accuracy and scanning time were obtained. In addition, a strong positive correlation between the simulated and experiment scan points is observed, proving the effectiveness of the developed scan planning method.

Table 1. Comparison results of edge line estimation accuracy on top surface and scanning time estimation results at the generated laser scanner locations

Laser scanner location	**Edge line estimation accuracy**			**Scanning time estimation**		
	Simulation	Experiment	Similarity	Simulation	Experiment	Similarity
P_1 (0m, 1m, 4m)	4.1 mm	5.1 mm	80.3%	408 sec	567 sec	71.9%
P_2 (1m, 1m, 4m)	3.6 mm	4.6 mm	78.2%	456 sec	587 sec	77.6%
P_3 (3m, 1m, 4m)	2.9 mm	4.0 mm	72.5%	504 sec	582 sec	86.6%
Ave.	3.5 mm	4.6 mm	76.1%	456 sec	578 sec	78.9%

5. CONCLUSION

This study presents a new scan planning approach using flat mirrors to enable rapid and accurate registration-free GQI of full-scale PC slabs. A mirror-aided GQI system using flat mirrors is proposed and a scan planning method is developed to determine the optimal locations of the laser scanner and flat mirrors. For validation, a series of simulation and experimental tests are conducted to investigate the performance of the proposed method. The test results show that around 80% similarity between the simulated data generated by the scan planning method and the experimental data was achieved, proving the effectiveness of the scan planning method. It is expected that the proposed system can be applied to real practice during the manufacturing and construction stages of prefabricated construction components.

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