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Evaluation of edge line estimation algorithms for accurate dimensional quality assessment of PC slabs

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ABSTRACT

Edge line estimation is an important task to ensure accurate dimensional quality assessment (DQA) for precast concrete (PC) slabs. For this task, there have been a few edge line estimation algorithms developed using point cloud data. This study aims to evaluate existing edge line estimation algorithms in order to determine an optimal algorithm for DQA of PC slabs. For evaluation, simulated scan points generated based on a geometrical model are used for detailed parametric study. A series of simulation and experimental tests are conducted for evaluating the DQA algorithms. The results show that the LSR2 algorithm provides a best DQA accuracy of 2.94 mm for DQA of PC slabs.

1. INTRODUCTION

Recently, digital technologies have been rapidly developed and adopted to all kinds of industries, offsite manufacturing and construction is popularly employed in the construction industry. One type of the examples is the production of precast components such as precast concrete (PC) slabs and precast girders (Polat 2010; Sacks et al. 2004). Compared to onsite construction, offsite construction based on prefabricated components offer clean and efficient practice (Sacks et al. 2004). However, one difficulty of offsite construction is the precise assembly between precast components, which is occurred during the construction stage onsite. To prevent this issue, precise dimensional quality control on individual components is very important because a large discrepancy between the as-designed and as-built dimensions of precast components could cause

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structure failures and construction delays (Birkeland et al. 1971; Josephson et al. 1999). Recently, non-contact sensing technologies such as laser scanning have been popularly used for DQA of precast components due to its natures of high accuracy and speed (Kim et al. 2014; Kim et al. 2016). Some studies proposed edge line estimation algorithms for DQA of prefabricated construction components based on laser scanning (Kim et al. 2014; Kim et al. 2016; Wang et al. 2016; Wang et al. 2019). However, there is no study that evaluates these edge line estimation algorithms, thus it remains unknown which kind of edge line estimation algorithm perform better to ensure accurate DQA of PC components.

To fill in the abovementioned research gap, this study aims to evaluate existing edge line estimation algorithms in order to determine an optimal algorithm for DQA of PC slabs. For evaluation, simulated scan points generated based on a geometrical model are used for detailed parametric study. A series of simulation and experimental tests are conducted for evaluating the DQA algorithms. The reminder of the paper is organized as follows. in Section2, related studies on various edge line estimation algorithms are presented. Section 3 presents the methodology of scan point simulation based on a geometrical model, followed by validation through detailed parametric study in Section 4. Finally, Section 5 ends with a brief summary of this study.

2. RALATED STUDIES

First, an edge extraction algorithm called ‘vector-sum’ algorithm (Kim et al. 2014) was proposed. The algorithm uses summation of the eight vectors $V(p_i)$ generated between each scan point (p_i) and its eight nearest neighboring points ${p_i^m}_{m=1\ldots8}$. If the summation of the eight vectors $V(p_i)$ of a point is larger than 2.5 times the point-to-point distance between two adjacent scan points, the reference point is regarded as an edge point. Otherwise, the reference point is classified as a non-edge point. Then, all scan points determined as edge points are used to line fitting using the least-squares fitting. After the line fitting, dimensional edge loss caused by the mixed pixel effect is compensated by the edge-loss compensation model proposed in Tang et al. (2009). For applicability investigation of the vector-sum algorithm, an extended version of the vector-sum algorithm combining with the RANSAC algorithm was proposed (Kim et al. 2016).

Later, two edge line estimation algorithms based on the least square regression called ‘LSR1’ and ‘LSR2’ were proposed in Wang et al. (2019). The new concept of creating virtual scan points outside edge lines was used in the study. The LSR1 algorithm first extracts last valid scan points positioned inside the edge line and then generates virtual scan points next to the last scan points but outside the edge line. Finally, the center points between the last valid points and the virtual scan points are used to fit a line using the least square regression. In addition, compared to the LSR1 algorithm, the LSR 2 algorithm is similar but different in terms of the data sets. The difference is that the data set for the LSR2 algorithm excludes mixed pixel scan points whereas the data set for the LSR1 algorithm includes mixed pixel scan points for line fitting.

Although those edge line estimation algorithms were separately developed for DQA of PC slabs, no study was conducted to evaluate the existing edge line estimation algorithms to enhance the DQA accuracy. Hence, this study evaluates the existing edge line estimation algorithms to select optimal algorithm for accurate DQA of PC slabs.

3. METHODOLOGY

Fig. 1 shows the overall scheme of the proposed simulation-based evalution of edge line estimation algorithms, consisting of three steps 1) simulation of scan points, 2) evaluation of DQA accuracy and 3) selection of optimal edge line estimation algorithm.

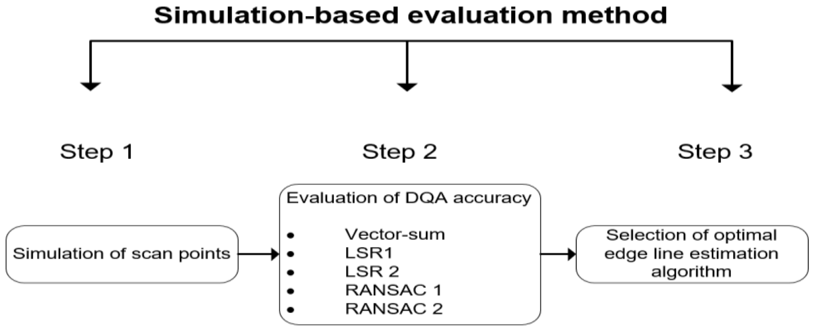


Fig. 1 Overall scheme of this study: The procedure for the simulation based evaluation of edge line estimation algorithms

3.1 Simulation of scan points

This step aims to develop a mathematical model to generate virtual scan points. Fig. 2 shows the mathematical model on a target object surface. With the line-of-sight characteristic of the laser scanner, the y position of the laser beam with a the vertical angle of V and a horizontal angle of H on the object surface can be calculated as:

$$y = d \times \frac{1}{cos\, H} \times tan\, V = d \times \frac{1}{cos(\Delta H \times i\ )} \times\times\, tan(\Delta V \times j) \quad (1)$$

where d is the perpendicular scanning distance between the object surface and the laser scanner. ΔV and ΔH are the vertical and horizontal angular resolution, respectively. Similar to the y position, the x position of the laser beam having the same vertical and horizontal angles (V and H) is calculated as

$$x = d \times \frac{1}{cos\, V} \times tan\, H = d \times \frac{1}{cos(\Delta V \times i)} \times tan(\Delta H \times j) \quad (2)$$

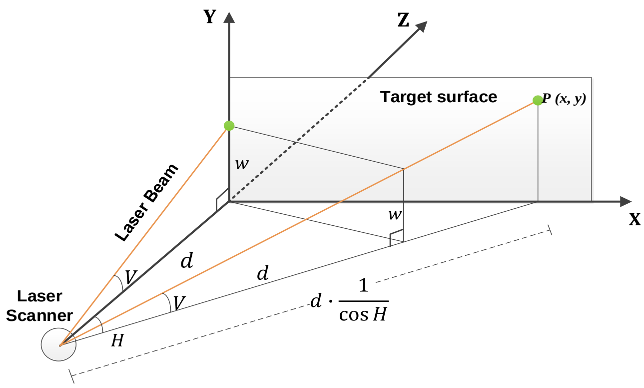


Fig. 2 Mathematical model on the target object surface.

3.2 Evaluation of DQA accuracy

This step aims to evaluate DQA accuracy of different edge line estimation algorithms. Here, five different edge line estimation algorithms are selected for evaluation, which are 1) vector-sum, 2) LSR1, 3) LSR2, 3) RANSAC1 and 4) RASNAC2. Note that similarly to the LSR1 and LSR2, the two algorithms of RANSAC1 and RANSAC2 use the RANSAC algorithm for line fitting and the difference between them is the data set used for line fitting.

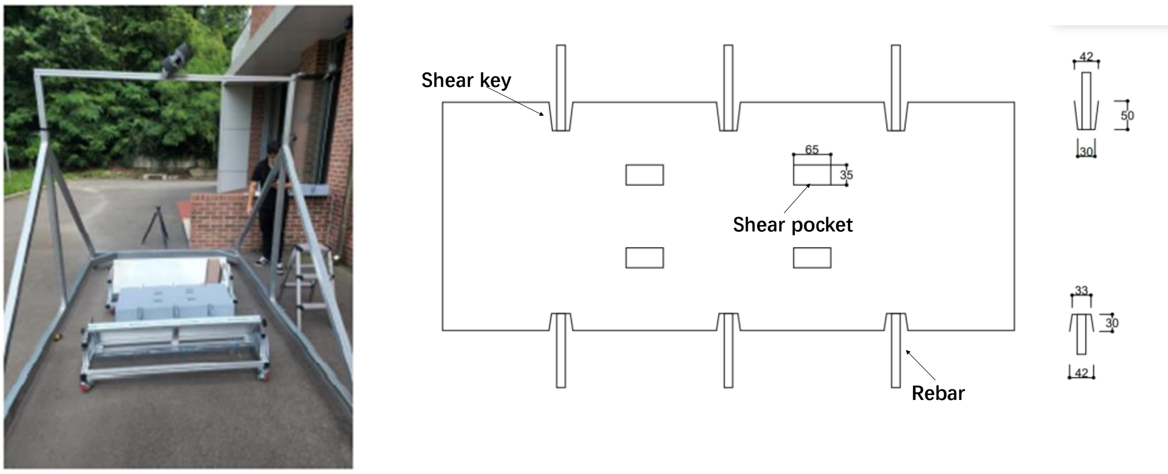
3.3 Selection of optimal edge line estimation algorithm

After evaluating the DQA accuracy of the five edge line estimation algorithms, the algorithm with the highest accuracy is selected as the optimal edge line estimation algorithm for DQA.

4. RESULTS

4.1 Description of test configuration and specimen

Fig. 3 shows a lab-scale PC slab with dimensions of 1000 mm (length)× 400 mm (width)×150 mm (height). In this study, a phase-shift TLS, FARO M70, was used to acquire scan points of the top surface of the specimen for comparison with simulation results. The laser scanner mounted on the steel frame is located above the center of the specimen with a scanning height of 2 m as shown in Fig.3(a). Fig. 3 (b) shows the dimensions of the top surface in the 2D top view. There are 4 shear pockets with the dimensions of 65 mm × 35 mm on the top surface of the specimen. In addition, shear keys and rebar are embedded on the longitudinal side surface of the specimen. In this study, two different angular resolutions of 0.036◦, and 0.072◦ were used to change scan density and investigate the effect of scan density.



(a) (b)

Fig. 3 Test configuration and dimensions of the lab-scale PC slab: (a) test configuration; and (b) dimensions of the top surface in 2D view.

4.2 Comparison of scan density

Simulated scan points are compared with the collected scan points from the experiment. Table 1 shows the comparison results between the simulated scan points and collected scan points in terms of number of points and scan density. On average, 8.38% and 9.92% discrepancy were obtained for the number of scan points and scan density, respectively. Therefore, there is a high similarity between the simulated and experimental scan points, proving the correctness of the geometrical model.

Table 1. Comparison of simulated scan points and collected scan points number of scan points and scan density

Incident angle	Angular resolution	**NO. of scan points** (pts)			**Scan density** (pts/cm^2)		
		Exp.	Sim.	discrepancy	Exp.	Sim.	discrepancy
0°	0.036°	269,736	226,982	15.85%	71,03	59,80	15.81%
		66,490	56,679	14.76%	17,85	14,44	19.12%
45°	0.072°	100,210	100,963	0.75%	26,79	27,56	2.81%
		24,614	25,161	2.17%	6,71	6,84	1.95%
Ave.		115,263	102,446	8.38%	72,570	58,338	9.92%

4.3 Selection of optimal edge line estimation algorithm

After the validation of the geometrical model, simulation data was used to evaluate the five edge line estimation algorithms. Fig. 4 shows an example of the edge line estimation result on the top surface of the specimen in simulation using the LSR2 algorithm. For optimal algorithm selection, the corner points determined as the intersection points of the extracted edge lines in Fig. 4 are used to compute the corner errors defined as the distance discrepancy between the estimated corners and the actual corners that was measured using a measurement tape. Note that the actual corners are used as ground-truth values as the specimen is precisely manufactured. Table 2 shows the comparison of corner errors among the five algorithms under varying angular resolutions and incident angles. It is observed that the LSR2 shows the best performance in overall than the others, so it was selected as the optimal edge line estimation algorithm for DQA of PC slabs.

Table 2. Comparison of Corner errors among the five edge line estimation algorithms under varying angular resolutions incident angles

Incident angle	**Angular resolution**	**Corner errors** (mm)				
		Vector-sum	LSR1	LSR2	RAN.1	RAN.2
0°	0.036°	1.61	2.49	1.83	2.55	2.09
	0.072°	3.18	4.01	2.73	4.81	3.77
45°	0.036°	2.60	3.08	2.66	3.90	3.25
	0.072°	5.16	5.27	4.54	6.46	5.69
Ave.		3.13	3.71	2.94	4.43	3.70

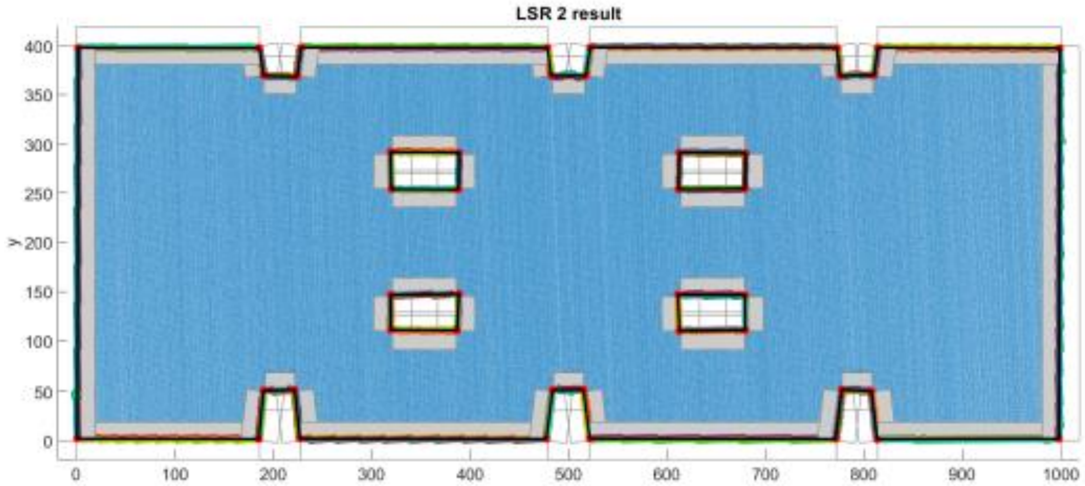


Fig. 4 An example of edge line estimation and corner extraction on the top surface of the specimen

5. CONCLUSION

This study presents a performance analysis to determine optimal edge line estimation algorithms among the five existing algorithms for DQA of PC slabs. For evaluation, simulated scan points generated based on a geometrical model are used for detailed parametric study. A series of simulation and experimental tests are and the results show that the LSR2 algorithm provides a best DQA accuracy of 2.94 mm for DQA of PC slabs. However, this study only analysis the edge line estimation algorithms for PC slabs. Further study is required to investigate the optimal edge lines estimation algorithms to enhance DQA on other construction components.

ACKNOWLEDGEMENTS

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