A VTA–ADM Framework for Real-Time Alignment Deviation Measurement in Precast Column Assembly Using Point Cloud–Image Fusion

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Abstract

Alignment control of grouted-sleeve connections is a critical yet labor-intensive step in precast concrete (PC) assembly. Current practice relies heavily on manual measurements before lifting and on experience-based corrections during hoisting, which makes deviation quantification slow, subjective, and difficult to digitalize. This paper presents a point cloud–image fusion method for automated alignment deviation measurement, designed for both pre-hoisting planning and in-hoisting monitoring. The method is organized into two coupled modules: (i) a virtual trial assembly (VTA) module that extracts sleeve and rebar assembly points, performs position inspection, and builds a trial-fit model to pre-check potential collisions; and (ii) an alignment deviation measurement (ADM) module that estimates the rigid transformation of the lifted component using three non-collinear feature points and computes the sleeve-to-rebar offsets in real time. To robustly localize the assembly points from structured-light point clouds, planar fitting, point projection, Hough circle detection, and density-based clustering are integrated. Experiments on a 3D-printed laboratory mock-up demonstrate sub-millimeter accuracy in sleeve/rebar feature extraction, alignment estimation within 3 mm. The proposed framework provides a practical path toward digital quality control for PC assembly with affordable sensing and lightweight computation.

Keywords –

Precast concrete; grouted sleeve connection; assembly quality; point cloud–image fusion; virtual trial assembly; alignment deviation

1 Introduction

Precast concrete (PC) construction has gained rapid adoption because it enables factory-controlled production, reduced on-site labor, and accelerated schedules. For load-bearing frames, grouted-sleeve connections between the precast column and the reserved rebars in the cap (or footing) are widely used [1-3]. However, the effectiveness of these connections depends strongly on alignment quality: excessive sleeve-to-rebar deviation can lead to collision, insufficient grout coverage, or forced bending of rebars, which in turn compromises structural performance and increases rework risks [4].

On construction sites, alignment checks are commonly conducted in two stages. Before hoisting, the arrangement of rebars is inspected by manual gauging and by installing temporary fixture plates [5]. During hoisting, workers continuously adjust the lifted element based on visual judgment, while measurements are difficult because the component moves and occlusions are frequent [6, 7]. These practices are time-consuming and provide limited quantitative records, making it hard to implement data-driven quality management [8]. Figure 1 illustrates the practical inspection challenge of grouted-sleeve connections in PC column assembly.

A number of sensing-based solutions have been explored for geometric inspection, including total stations, laser trackers, photogrammetry, and 3D scanning [9-11]. Although high-end laser scanning can deliver high accuracy, its cost and operational requirements often prevent routine use in PC assembly. Vision-based methods are more affordable, yet they are sensitive to illumination, require clear markers, and struggle with small circular openings and dense rebar layouts [12, 13].

To bridge this gap, we propose an automated method that fuses 3D point cloud data with 2D imagery to precisely quantify alignment deviations during precast concrete (PC) column assembly. The method supports both pre-hoisting assemblability assessment and in-hoisting positioning measurement, enabling high-precision automated assembly under a stringent 3 mm tolerance constraint. It comprises two modules. (1) Virtual Trial Assembly (VTA): This module evaluates pre-hoisting assemblability by automatically estimating pre-assembly misalignment. It preprocesses point clouds of rebars and sleeves, projects them into an image representation, extracts key assembly points via Hough Transform (HT) circle detection [14], and computes pre-assembly errors using Extended Orthogonal Procrustes Analysis (EOPA) [15]. (2) Alignment Deviation Measurement (ADM): Leveraging three non-collinear assembly feature points, this module automatically determines the deviation between the PC column and connected rebars during hoisting to guide high-precision on-site alignment. Collectively, the proposed framework provides a methodological and technical basis for intelligent hoisting and precision assembly of grouted-sleeve-connected PC columns.

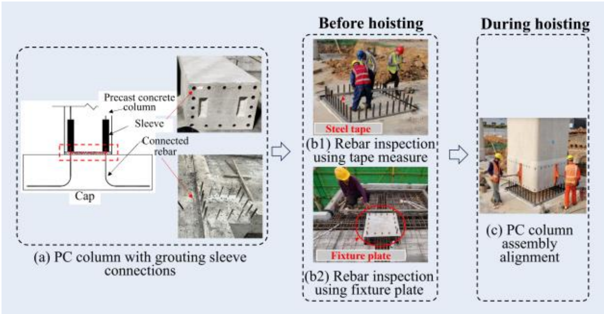


Figure 1. Typical grouted-sleeve connection and on-site alignment inspection stages in PC column assembly

2 Method

This study presents an automated approach to quantify assembly alignment deviations in precast concrete (PC) components by fusing structured-light 3D point clouds with 2D image representations (Figure 2). The framework comprises two complementary modules: Virtual Trial Assembly (VTA) and Alignment Deviation Measurement (ADM).

The VTA module is executed prior to hoisting to answer whether the component can be assembled and, if not, why. Specifically, it (1) extracts sleeve and rebar center points from the scanned data, (2) checks their positional consistency with the design layout to identify fabrication or handling-induced offsets, and performs a VTA by aligning sleeves and rebars to predict insertion feasibility. This VTA enables early detection of collision-prone or tolerance-violating alignment, thereby indicating whether the assembly is feasible and pinpointing the sources of potential failure (e.g., excessive misalignment beyond the allowable tolerance).

The ADM module is executed during hoisting to determine how much the system is currently misaligned and how it should be corrected. Once the lifted column enters the camera's capture range, ADM (1) estimates the column pose using three non-collinear sleeve centers as rigid-body references, and projects the corresponding rebar key points onto the column base plane, and (2) computes sleeve-to-rebar deviations as quantitative horizontal offsets. These outputs provide actionable, real-time deviation measurements that can directly guide fine alignment adjustments until the deviations fall within the assembly tolerance.

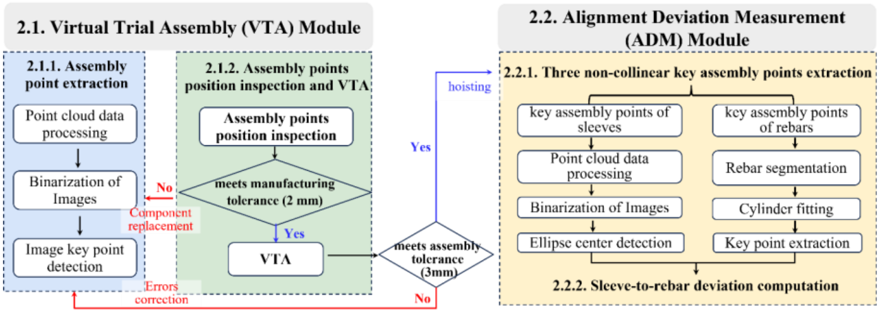


Figure 2. Overview of the proposed framework with virtual trial assembly (VTA) and alignment deviation measurement (ADM)

2.1 Virtual Trial Assembly (VTA) Module

The VTA module targets the pre-assembly stage before hoisting. It generates a uniform array of assembly points from the precast column and connected rebars, evaluates their positional quality, and constructs a virtual model to detect possible collisions. The method is specifically divided into two steps: (1) assembly point extraction; and (2) position inspection and VTA.

2.1.1 Assembly Point Extraction

For the column bottom, the local point cloud around each sleeve opening is first segmented by a pass-through filter. A dominant plane is fitted by Random Sample Consensus (RANSAC) algorithm to isolate the bottom surface [16]. The inlier points are orthogonally projected to the plane to form a dense 2D cloud plane, which is then binarized so that sleeve openings appear as circular voids.

Hough circle detection is employed to acquire the 2D circle parameters, and the circle centers are subsequently back-projected into 3D to determine sleeve centers, as illustrated in Figure 3.

For the connected rebars, the point cloud is filtered by height to suppress background and then clustered using Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm in 3D space [17]. Each cluster represents a rebar segment. The rebar centerline is established through cylinder fitting, with its top-center point designated as the assembly point. These operations are designed to be insensitive to partial occlusions and to avoid reliance on artificial markers.

To extract assembly points from as-designed 3D models, they are first converted into PCD format. A pass-through filter is then applied to isolate the edge points of the column's bottom sleeves and the rebars' top surfaces. Finally, the geometric centers are determined by computing the average values of these filtered points, as shown in Figure 4.

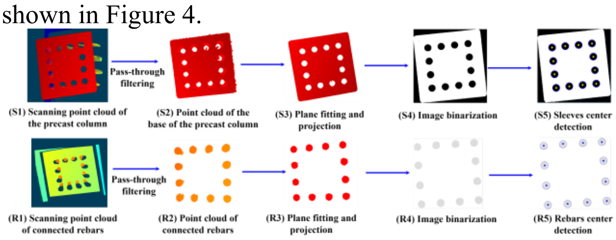


Figure 3. Extraction of assembly points for the precast column and associated rebars in the as-built model

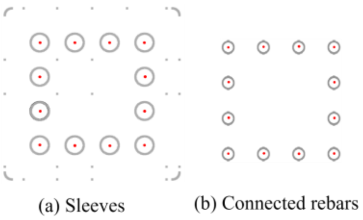


Figure 4. Extraction of assembly feature points for the precast column and associated rebars in the as-designed model

2.1.2 Position Inspection and VTA

The positional mismatch between grouting sleeves and connected rebars in precast columns significantly complicates the alignment process during on-site hoisting. While the dimensions of components are verified ex-factory, positional misalignments resulting from collisions during transportation and handling remain a primary concern. To address this, the Extended Orthogonal Procrustes Analysis (EOPA) algorithm is employed to assess positional accuracy and perform Virtual Trial Analysis (VTA). EOPA minimizes the least-squares deviation between two corresponding point sets to determine the optimal rigid body transformation. Given a target point set $Y_{c\times 3}$ and a source point set $X_{c\times 3}$ (where c denotes the number of alignment feature points), the transformation is defined as:

$$Y = XR + jt^{\mathrm{T}} + E \tag{1}$$

where $R_{3\times 3}$ is a rotation matrix, $t_{3\times 1}$ is a translation vector, j is a unit vector (1, 1, ... , 1) $^{\mathrm{T}}$, and E is the error matrix. The objective is to calculate the transformation parameters R and t that minimize the squared Euclidean norm of E:

$$\min\left\{\left\| XR + jt^{\mathrm{T}} - Y \right\|^2\right\} \tag{2}$$

This optimization problem is solved using Singular Value Decomposition (SVD) based on the properties of orthogonal matrices. The calculated deviations are then evaluated against specific tolerance standards in two stages. First, for the position inspection of the sleeves and connected rebars, the as-built assembly points are aligned with their theoretical design positions, as shown in Figure 5. According to the Standard for tolerances for PC components (T/CCES 30-2022), the deviation of the centerline positions must not exceed 2 mm to verify component integrity before hoisting. Second, VTA is conducted to simulate the field installation process. In this stage, the algorithm aligns the assembly points of the connected rebars (source X) with the sleeves of the precast column (target Y) derived from the as-built models, as shown in Figure 6. Even if fabrication errors are within individual tolerances, relative deviations may prevent successful connection. Therefore, in accordance with the Technical Standard for Assembled Buildings with Concrete Structure (GB/T 51231-2016), the alignment deviation during this virtual trial must be within 3 mm. If collisions or excessive deviations are detected, the components must be adjusted or replaced to ensure the final assembly meets standard requirements.

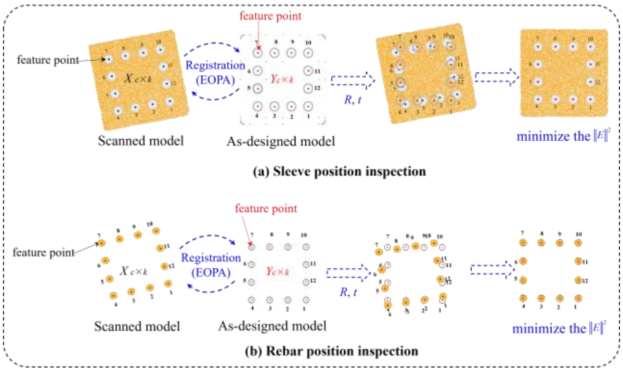


Figure 5. Sleeve and rebar position inspection

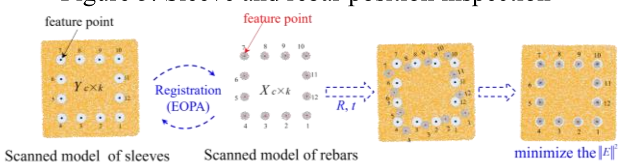


Figure 6. VTA of sleeve and rebar

2.2 Alignment Deviation Measurement (ADM) Module

The ADM module is designed to quantify the instantaneous sleeve–rebar misalignment during hoisting and provide actionable deviation outputs for on-site fine alignment. To achieve stable and effective positional deviation measurement, three pairs of spatially well-separated, non-collinear rebars were selected. Their top surface centers and corresponding sleeve centers serve as key assembly points for precast columns. These points uniquely determine three-dimensional rigid-body positional deviations while avoiding interference from obstructions. Therefore, the core task of this section is to resolve alignment issues by extracting three key points and calculating deviations. This method is achieved through two steps: (1) extracting key assembly points from sleeves and connected rebars; (2) calculating alignment deviations between sleeves and connected rebars.

2.2.1 Extraction of Three Non-collinear Key Assembly Points

This subsection aims to extract the key assembly points of the three pairs of sleeves and rebars during the hoisting process, enabling comparison of positional deviations between sleeves and rebars within the same coordinate system.

For the precast column (see Figure 7 (a)), the raw point cloud captured by a structured light camera is first filtered to isolate the bottom assembly control plane. The RANSAC algorithm fits a plane equation $ax + by + cz + d = 0$ to the bottom surface. Points within this plane are projected orthogonally and rasterized into a 2D binary image. The Hough Transform is then employed on the processed image to identify the centers of the sleeves. To ensure accurate extraction and minimize false positives, the algorithm parameters were explicitly calibrated based on the known physical geometry of the sleeves (D = 26 mm). Specifically, the minimum and maximum detection radii were set to 12 and 15 pixels, respectively, the minimum center distance was set to 40 pixels, and the accumulator threshold was set to 30. These 2D image coordinates (u, v) are back-projected into 3D space (X, Y, Z) using the camera's intrinsic parameters (f_x, f_y for focal length and c_x, c_y for principal points) and the measured depth Z via the pinhole model:

$$X = (u - c_x)\frac{Z}{f_x},\ \ Y = (v - c_y)\frac{Z}{f_y} \tag{3}$$

Parallel to this (see Figure 7 (b)), the connected rebars are processed to locate their top geometric centers. The point cloud is segmented into individual rebar clusters using DBSCAN. To ensure distinct clustering and robustly filter out background noise, the neighborhood search radius was set to 40 mm, deliberately smaller than the physical spacing of 50 mm between adjacent rebars and the minimum number of points to form a core point was set to 50. The Euclidean distance threshold is calibrated to the physical spacing between adjacent rebars to ensure distinct clustering. For each cluster, RANSAC is utilized to fit a 3D cylinder model, defined parametrically as:

$$\mathrm{L}(t) = \mathrm{p}_0 + t \cdot v \tag{4}$$

where p_0 is a point on the axis and v is the direction vector.

The intersection of this axis with the fitted plane of the rebar's top surface determines the rebar center. Finally, to define the pose for alignment, three specific corresponding points are selected from the extracted sets of sleeve and rebar centers: those with the maximum x-coordinate, minimum x-coordinate, and minimum z-coordinate in the camera coordinate system.

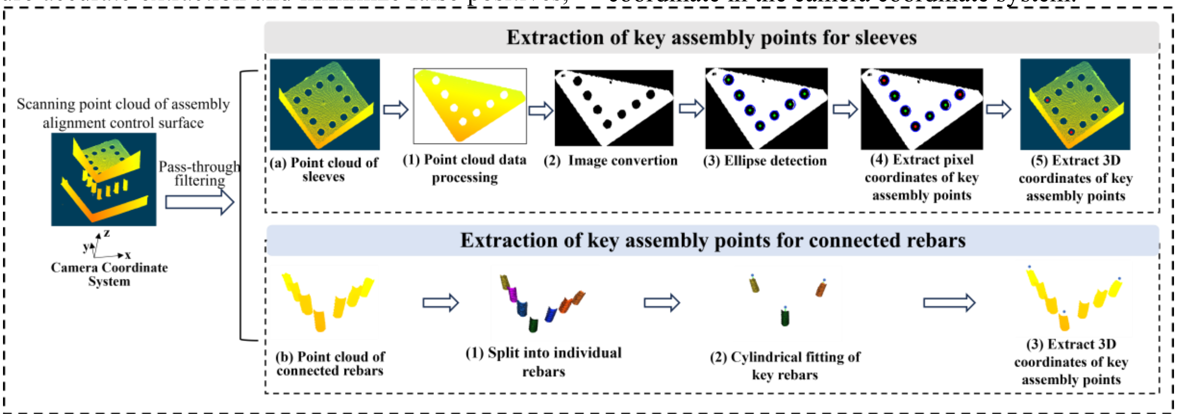


Figure 7. Flowchart for extracting key assembly points of sleeves and connected rebars

2.2.2 Sleeve-to-Rebar Deviation Computation

This subsection aims to compute quantitative alignment deviations between each sleeve and its corresponding rebar after extraction of assembly points, providing both magnitude and direction to guide corrective movements, which can be shown in Figure 8. Following the spatial localization of the key points, the alignment quality is quantified by projecting the rebar coordinates onto the reference plane of the precast column. Let the three extracted key assembly points on the precast column be denoted as $P_{c,\ i}$ and the corresponding points on the connected rebars as $P_{r,\ i}$, where $i \in \{1, 2, 3\}$. To decouple vertical gaps from horizontal misalignment, each rebar point $P_{r,\ i}$ is orthogonally projected onto the fitted plane of the column's bottom surface, yielding the projected coordinates $P'_{r,\ i}$. The alignment deviation d_i is then defined as the Euclidean distance between the specific sleeve center and the projected rebar center.

$$d_i = \left\| P_i^c - P_i^{r'} \right\|_2 \tag{5}$$

These deviation values d_i serve as indicators of the horizontal translational offset between the component interfaces, providing the necessary metric to guide corrective adjustments during the assembly process (see Figure 8).

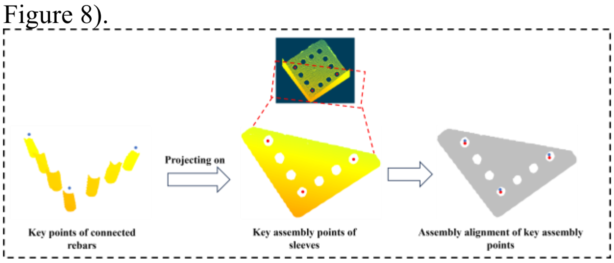


Figure 8. Flowchart for calculating alignment deviation

3 Experimental Validation

To verify the effectiveness of the proposed method, feasibility tests were conducted in a laboratory setting. Due to the high risk associated with hoisting at construction sites, laboratory verification provides the necessary data to optimize on-site application. 3D-printed models of the precast column and connected rebars were custom-designed to simulate the actual assembly scenario (see Figure 9). The experiment was divided into two parts: (1) VTA of the precast column before hoisting, and (2) alignment deviation measurement during the hoisting process.

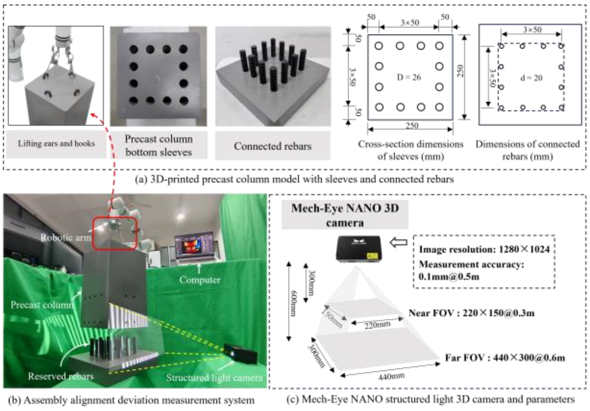
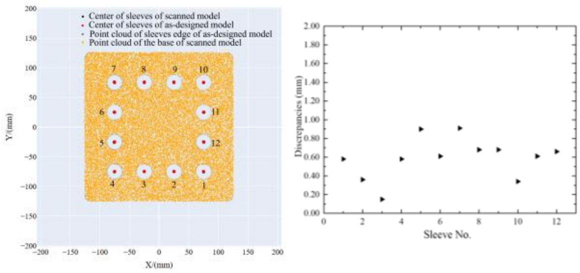


Figure 9. Assembly alignment deviation measurement system for precast column

3.1 VTA Experimental Results

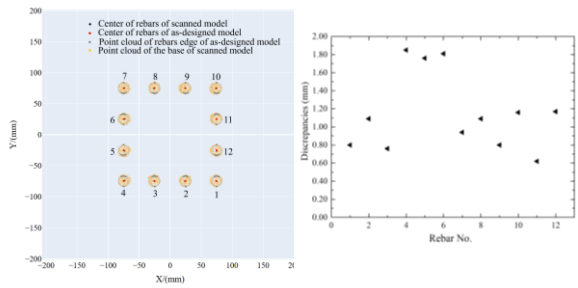
3.1.1 Assembly Point Position Checking

To validate the effectiveness and accuracy of the proposed method for detecting the positions of sleeves and rebars assembly points before precast column hoisting, two alignment verification tests were conducted. The EOPA algorithm was employed to align the scanned models of the connected rebars and sleeves with their respective design models. As demonstrated in Figures 10 (a) and 11 (a), an analysis was conducted on the positional deviations between the bottom sleeve or connection reinforcement of the precast column and their respective design models. The quantitative results presented in Figures 10 (b) and 11 (b) demonstrate that the positioning deviations of both sleeves and rebars were meticulously regulated within the 2 mm tolerance stipulated by the specifications. To validate the method's accuracy, two templates were fabricated to replicate the actual cross-section dimensions of sleeves and connected rebars at a 1:1 scale. The alignment of these templates with the centers of mass of their respective design models, ensuring no rotation. Based on this alignment, the alignment deviations were measured using a vernier caliper for both components, serving as the true alignment deviation values. Experimental results demonstrate good agreement between the method's predicted alignment deviations and the true values. The mean absolute error for sleeve position detection was 0.12 mm, with a root mean square error of 0.13 mm. For rebar position detection, the average absolute error was 0.25 mm, with a root mean square error of 0.26 mm. Therefore, the proposed method effectively detects positional deviations in sleeve and rebar assembly points, laying the foundation for subsequent virtual trial assembly of sleeves and rebars.



(a) Visualization of alignment deviation (b) Alignment deviation

Figure 10. Alignment deviation of sleeves between the scanned and the as-designed models

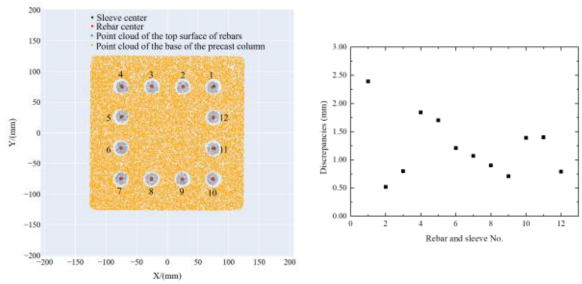


(a) Visualization of alignment deviation (b) Alignment deviation

Figure 11. Alignment deviation of connected rebars between the scanned and the as-designed models

3.1.2 VTA of the Sleeves with the Connected Rebars

To validate the effectiveness and accuracy of the proposed Virtual Trial Assembly (VTA) method, a comparative verification experiment was conducted. This experiment involved both VTA and physical trial assembly. In the VTA, the EOPA algorithm was utilized to align connected rebars with sleeves based on the scanned model. The visualization of alignment deviations (see Figure 12 (a)) enabled the detection of potential collisions where deviations exceeded the allowable tolerance. Figure 12 (b) provides a detailed representation of the alignment deviations between the centers of 12 sleeves and their corresponding rebars. The maximum deviation observed was 2.39 mm, the average deviation was 1.23 mm, and the standard deviation was 0.53 mm. It was determined that, given the maximum projected distance remained below the allowable tolerance of 3 mm, the component was deemed to be theoretically suitable for assembly. To validate these predictions, two model plates were fabricated at a 1:1 scale, with strict replication of the dimensions of the precast column's bottom sleeve cross-section and the connected rebars' top surface. These plates facilitated a physical trial assembly where the centers were aligned without relative rotation, and actual positional deviations were measured using a vernier caliper to establish ground truth values. The comparison results demonstrate a strong alignment between the VTA predictions and the ground truth values. Specifically, the mean absolute error between the two is 0.12 mm, and the root mean square error is 0.15 mm. The high degree of consistency observed between the predicted and measured values serves to substantiate accuracy of the proposed method. Therefore, by identifying optimal rebar positions and potential collision risks before hoisting, the method allows for necessary recalibration, thereby significantly mitigating the risk of on-site rework due to misalignment.



(a) Visualization of alignment using VTA (b) Alignment deviation errors using VTA

Figure 12. Comparison of alignment deviation between VTA method and fixture plate

3.2 Alignment Deviation Measurement Experiments

To validate the effectiveness of the proposed alignment deviation measurement method, the 3D-printed precast column models and corresponding connected rebar models were used as test objects. The robotic arm was first set to raise the precast column model to a height of 30 mm above the top of the connected rebar. The structured light camera was simultaneously positioned along the diagonal extension, as depicted in Figure 9 (a), at a distance of 300 mm from the first connected rebar. Subsequently, the point cloud data of the precast column and the connected rebar were acquired. The acquired point cloud data were processed using the key assembly point extraction algorithms for sleeves and connected rebars presented in this paper, respectively, to derive the three-dimensional coordinates of the centers of the left, middle, and right sleeves, as well as the centers of the corresponding connected rebar tops. The precast column model often maintains a vertical orientation due to its own weight, resulting in a bottom surface that is generally horizontal. To determine the horizontal deviation between the key assembly points of the sleeves on the bottom surface of the precast column and the corresponding key assembly points of the reserved rebars, the key assembly points of the reserved rebars were initially projected onto the plane of the bottom surface of the precast column. The projected coordinates are presented in Table 1. The horizontal deviation was determined by the distance between the two projected positions, whereas the actual deviation was measured using a vernier caliper. Table 1 indicates that the mean deviation between the key assembly points of the left, center, and right sleeves and their respective key assembly points of the reserved rebars is 0.33 mm, thereby meeting the assembly alignment deviation accuracy requirement of 3 mm as stipulated in the code.

Table 1. Horizontal deviation measurement results of key assembly points for precast column and reserved rebars in camera coordinate system

Key assembly points	3D coordinates of key assembly points projected on the precast column's bottom plane			Calculated deviation (mm)	Actual deviation (mm)	Measured error (mm)	Average error (mm)	Time (s)
	x (mm)	y (mm)	z (mm)					
Left sleeve	-84.7	34.5	410.4	0.90	0.50	0.40	0.33	0.240
Left rebar	-84.3	34.4	409.6					
Middle sleeve	17.9	8.5	303.5	0.70	0.50	0.20		
Middle rebar	18.1	9.0	303.9					
Right sleeve	127.1	34.1	402.2	1.00	0.60	0.40		
Right rebar	126.1	34.0	402.0					

The ADM module is ultimately designed to provide precise alignment deviation input for robot-assisted automated installation using an iterative "look-and-move" strategy. Since alignment requires multiple "look-and-move" cycles for continuous fine-tuning, the system's real-time capability is evaluated by its single-frame processing latency. Executed on a standard computer (Intel Core i5-11400H CPU, 16 GB RAM), the average processing time for a single complete computational cycle is 0.24 s. This sub-second latency ensures rapid visual feedback for the robotic effector, validating its feasibility for real-time closed-loop control in automated construction.

4 Conclusions and Future Works

This paper presented a point cloud–image fusion framework for automated alignment deviation measurement in precast column assembly. The key idea is to couple a pre-hoisting virtual trial assembly with a during-hoisting alignment deviation measurement, enabling both early collision screening and real-time quantitative feedback. By combining plane fitting, projection-based binarization, Hough circle detection, and density-based clustering, the framework robustly extracts sleeve and rebar assembly points from local structured-light scans. Experiments demonstrated sub-millimeter feature extraction and alignment estimation within 3 mm. The method provides a practical approach for digital quality control of grouted-sleeve connections and can be integrated into routine PC assembly workflows.

While the current laboratory-scale experiments validate the fundamental feasibility of the proposed framework, several limitations remain to be addressed in future work to better position its contribution for real-world automated construction.

First, the current scope is primarily limited to single rectangular columns connected by grouted sleeves. Future research will aim to evaluate the propagation of local pose deviations to adjacent members and extend the generalizability of the method to other precast components (e.g., beams and slabs) and varied connection configurations.

Second, while the current laboratory experiments demonstrate the feasibility of the proposed method under a specific baseline condition (camera distance of 300 mm, hoisting height of 30 mm), the dynamic distances and potential environmental occlusions during actual hoisting can significantly affect the overall measurement performance. Due to the scope limitations of this conference paper, a comprehensive parametric analysis investigating the impact of varying camera distances, dynamic heights, and varying degrees of occlusion on measurement accuracy will be systematically addressed in our future work.

Third, transitioning this vision-based method to real-world construction sites presents practical environmental challenges. Future full-scale component testing must address dynamic occlusions, severe lighting variability, and environmental sensor noise by incorporating multi-view setups, optical filtering, and advanced dynamic point cloud denoising algorithms. Ultimately, the vision of this framework is to provide precise, sub-second latency sensory input for robot-assisted automated installation. Future work will integrate this measurement system into a closed-loop "look-and-move" robotic control strategy, facilitating the transition toward fully autonomous precast concrete construction.

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