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A 3D Virtual Assembly Method for Cable-Stayed Bridge Closure Using Laser Scanning

Yan Xu[1], Zhenzhen Cao[2]
[1] Jiangsu Key Laboratory of Mechanical Analysis for Infrastructure and Advanced Equipment, Southeast University, Nanjing 210096, China.
[2] School of Civil Engineering, Southeast University, Nanjing 210096, China.
email: xuyan0909@live.com, czz110909@163.com

ABSTRACT: The mid-span closure segment assembly of a cable-stayed bridge after cantilever construction traditionally relies on using a total station to measure the longitudinal distances of key control points to determine the closure trimming length. This approach neglects the rotation of the cantilever section, reduces the inherently three-dimensional (3D) assembly problem to a one-dimensional (1D) longitudinal assembly. To overcome this limitation, this paper presents a 3D virtual pre-assembly method for the closure segment based on point clouds captured from a single station. An efficient and accurate two-stage registration method based on 2D image matching and 3D visibility simulation was developed to align incomplete measured point clouds with the design model. The estimated poses of the two cantilever ends were used for the virtual assembly of the closure segment. An optimization model for 5-DOF geometric information of the closure segment was established and calibrated using a particle swarm optimization. The proposed method was validated during the construction monitoring of a large-span railway cable-stayed bridge, demonstrating its reliability and practical effectiveness.

KEY WORDS: Virtual Assembly, Laser Scanning, Point Cloud Registration

1 INTRODUCTION

Cable-stayed bridge closure marks the moment when two independent cantilevers become a single, continuous load-carrying system. To achieve the desired stress redistribution and deck profile, engineers must monitor the closure joint during the 48 h immediately preceding installation, capturing temperature-induced movements and determining the match-cut length of the closure segment with millimetre-level precision. Traditional construction monitoring relies on total-station surveys of a handful of control points on each cantilever tip to estimate the longitudinal gap. Although well established, this point-wise procedure is labour-intensive, prone to human error, and often too slow for modern fast-track schedules. Terrestrial laser scanning (TLS), by contrast, can acquire a dense, full-field 3-D point cloud of the entire closure region in a single scan, providing sub-centimetre accuracy and a far more comprehensive geometric record.

Over the past decade, researchers have explored TLS-enabled “virtual pre-assembly” workflows in bridge construction, focusing on reducing geometric deviations and optimizing prefabricated component assembly. Zhou et al. [1] proposed the virtual trial assembly method for prefabricated steel components in scenarios like bridge construction. It integrates high-precision point cloud registration, reverse BIM construction, and finite element analysis to accurately predict geometric shapes and stress states in prefabricated components. Li et al. [2] developed an automatic modeling approach for creating as-built prefabricated component models from laser-scanned data, specifically for virtual trial assembly. Liu et al. [3] develops an automated virtual trial assembly framework for large and complex steel members, integrating terrestrial laser scanning and BIM to improve geometric accuracy, streamline assembly point extraction, and enable precise geometric quality inspection of bending and torsional deviations. Zhang et al. [4] introduced an automated virtual trial assembly framework for large steel members with bolted connections, leveraging multiscale point cloud fusion to achieve submillimeter precision in feature extraction, registration, and assembly deviation analysis. Li et al. [5] proposed a virtual pre-assembly method utilizing 3D laser scanning technology to predict alignment of large-span segmental precast assembled concrete cable-stayed bridges under stress-free conditions, effectively shortening construction time, reducing complexity, and enhancing precision in the assembly process.

Despite the progress achieved in prior studies, significant challenges still remain. First, current fit-up calculations seldom account for the local downward deflection of the free cantilever tips under self-weight, thermal gradients, or wind loads, leading to non-vertical end faces at the time of measurement. Second, by collapsing millions of points into a few targets, valuable shape information is discarded. To address these gaps, this study introduces a 3D virtual-assembly method for cable-stayed-bridge closure that capitalises on high-resolution TLS. After all segments except the closure slab are erected, a TLS survey simultaneously captures the full geometry and relative pose of the two cantilever ends. A particle-swarm-optimisation–based virtual assembly routine then searches the point-cloud pair for the closure segment length and installation attitude that minimise global deck discontinuities. The method was validated during the closure of a cable-stayed bridge in Zhejiang Province, China, where it delivered rapid, centimetre-level predictions that aligned with field measurements. Ultimately, the goal is to leverage complete 3-D geometry and relative pose information to predict—before any on-site cutting—the optimal closure-segment length and pose, thereby streamlining cable-stayed bridge completion and enhancing construction quality control.

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2 METHODOLOGIES

Traditional closure practice measures only the longitudinal gap between the two cantilever tips and match-cuts the segment vertically, reducing a fundamentally 3-D structural-assembly problem to a 1-D splice. Because this approach ignores the true pose of the cantilever end sections (rotations and offsets), it struggles to meet today's mm-level accuracy requirements.

To overcome these limitations, we develop a point-cloud-driven virtual pre-assembly workflow consisting of three core stages (Figure 1).

In the first stage, each cantilever tip is scanned in situ, yielding dense but incomplete point clouds that capture deck edges. A synthetic point cloud generated from the as-designed numerical model is then rigidly aligned to the measured data via an iterative closest-point procedure, producing a 3D transformation matrix that maps design space to the bridge's physical coordinate frame. This registration not only reconciles deviations due to construction tolerances but also embeds the design geometry in the same reference frame as the field measurements.

The second stage performs virtual pre-assembly. The meshed design models of the two cantilever tips are transformed with the previously obtained matrix and imported into a physics-aware simulation environment. A particle-swarm-optimization solver searches the six-degree-of-freedom space to minimize the surface misfit between opposing tips, rapidly converging to a sub-mm pose match. Because the algorithm explores both translational and rotational degrees of freedom concurrently, it reveals subtle misalignments that would otherwise remain undetected under one-dimensional gap measurements.

In the final stage, the optimized virtual pose is used to derive the manufacturing and installation parameters of the closure segment. After correcting for construction-stage temperature effects, the workflow outputs the optimal match-cut length, the required bevel angle of the end faces, and the spatial orientation necessary for installation. These data provide fabricators with precise cutting instructions and give field crews an accurate set-out for lifting and welding, thus shortening decision cycles while ensuring that closure is achieved within the stringent tolerances demanded by fast-track bridge construction.

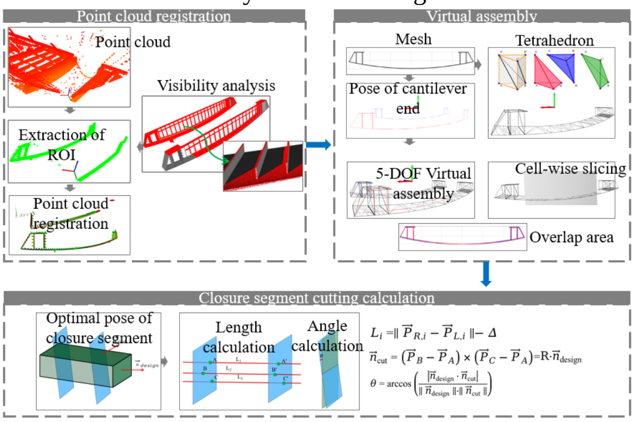

Figure 1. Flowchart of the proposed method for closure segment cutting calculation.

3 FIELD TEST ON A CABLE-STAYED BRIDGE

The proposed virtual-assembly workflow was validated on a cable-stayed bridge crossing on the Fuchun River in Hangzhou, Zhejiang Province, China. The structure features a mixed-height, H-shaped pylon arrangement and a hybrid steel–concrete deck. Span configuration proceeds from the west abutment as 62.395 m + 97 m + 300 m + 46 m + 30 m, giving an overall length of 535.395 m. The downstream pylon rises 141.5 m above foundation level, whereas the upstream pylon is 92 m high (see Figure 2).

The 300 m main span employs a composite section in which a U-shaped steel box girder is integrally connected to a cast-in-place concrete deck slab, yielding both bending stiffness and fatigue durability. Construction of this span followed the free-cantilever method: modular box-girder segments were symmetrically erected from each pylon, forming two outward-growing cantilevers. When the remaining gap diminished to less than a single segment, a closure unit was installed using the thermal-expansion technique to create a continuous load path. The segments immediately adjacent to the closure piece are labelled MG15 on the south-east cantilever and MD09 on the north-west cantilever. This full-scale construction scenario offered a realistic test bed for examining the accuracy and efficiency of the TLS-driven virtual pre-assembly method under field conditions.

Figure 2.Tested bridge for closure in construction

A RIEGL VZ-400i terrestrial laser scanner was deployed to acquire high-density point clouds of the opposing cantilever tips. The instrument offers a ranging window of 0.5 – 800 m and a single-shot accuracy of ±5 mm; for this test the pulse-repetition frequency was set to 1.2 MHz, while the full 360° horizontal and 100° vertical fields of view were enabled. To maximize coverage of the local cross-section, the scanner was rigidly mounted 1.6 m above the deck on the outboard edge of segment MD09 and levelled with its optical axis parallel to the bridge centerline. From this vantage, a single sweep captured the entire end face of the MD09 tip together with the mating surface of segment MG15 across the closure gap, yielding a unified dataset that preserves both geometry and relative pose for subsequent virtual pre-assembly processing.

Figure 3 depicts a representative time step of the raw point-cloud data. Because each sweep originates from a single scanner station, the TLS captures only the outward-facing portions of the two cantilever tips; one tip is almost complete, whereas the opposite tip contains only a narrow chord of the full cross-section. To isolate the geometric cues most relevant for alignment, the cloud is first segmented by fitting a best-fit plane to the deck-edge points of each tip and then retaining the points within a narrow band around that plane. The result shown in Figure 4 is a pair of sparsely sampled, partially visible cross-sections that serve as registration targets.

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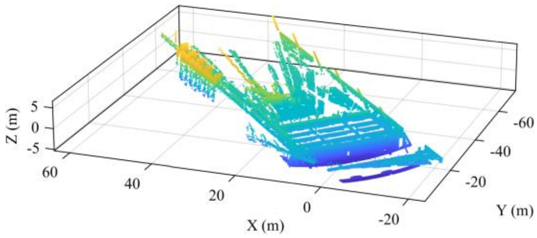

Figure 3. Raw point cloud of the cable-stayed bridge captured with the TLS.

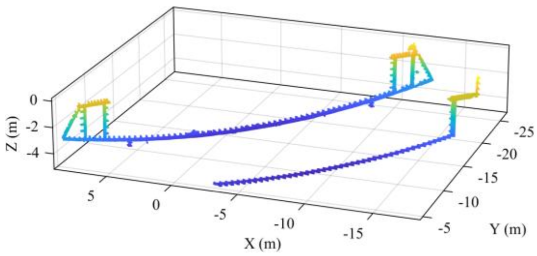

Figure 4. Filtered cantilever-tip cross-section extracted from the TLS data.

Iterative closest point (ICP) requires a reasonably accurate initial transform to avoid convergence to local minima. It is challenge to deal with the two targets share only limited overlap. To generate a robust starting estimate, the extracted cross-sections are orthogonally projected onto an image plane and converted to binary occupancy maps. A phase-correlation matcher is then applied to the two images, yielding translational shifts and in-plane rotations with sub-pixel precision; these parameters are back-projected into 3D space to construct the initial rigid-body transform.

Directly registering the measured cloud to the full design model is computationally inefficient and prone to bias because large portions of the as-designed surface are invisible in a single scan. We therefore employ a ray-casting routine to generate a virtual scan of the design model that mimics the scanner's actual position and field of view. The synthetic cloud retains only those facets that would be visible to the TLS under identical conditions, producing a down-sampled "design-congruent" dataset whose completeness closely matches that of the field measurement. ICP is then executed between the real and virtual point clouds, with the phase-correlation transform as its initialization. After registration, the measurements of control point distances were extracted from the TLS data and compared with those obtained from the total station. As shown in Figure 5, the distance errors for all 17 control points are within 10 mm.

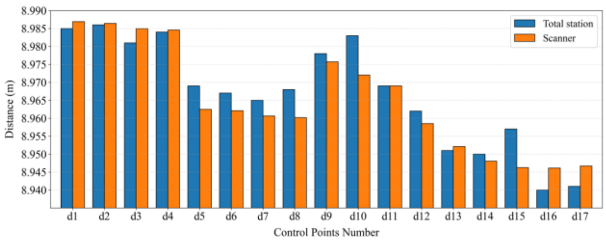

Figure 5. Comparison of control point distance measurements at cantilever beam ends using total station and TLS.

Once the spatial poses of the two cantilever tips have been fixed, the search for the best installation strategy can be formulated as a stand-alone optimization problem. A closure segment of ample stock length is first inserted between the tips in a nominal configuration that deliberately intersects both end faces. Because high-quality welding demands near-perfect geometric agreement at each splice plane, we evaluate every candidate pose by the overlap area—the common surface shared by the closure-segment end face and its mating cantilever section.

To automate the search, we couple the point-cloud pose information with the 3D CAD model of the closure segment and cast the task as a 5-DOF optimization: three translational components and two rotational angles around the local horizontal axes. The remaining rotation about the longitudinal axis is fixed to maintain deck camber continuity. A PSO scheme explores the 5-DOF space, beginning from a physically reasonable initial guess derived from the measured gap and the nominal bridge geometry. During each PSO iteration the algorithm updates the candidate pose, clips the closure segment to the planes of the two cantilever tips, and computes the resulting overlap areas. The fitness function is defined as the negative sum of these areas.

Convergence of the swarm yields the pose that maximizes simultaneous overlap at both interfaces. From the converged configuration the algorithm extracts two quantities required for fabrication and erection: (i) the match-cut length, obtained by measuring the distance between the optimally aligned splice planes, and (ii) the six-parameter installation pose, which prescribes the precise translation and orientation of the trimmed closure segment in the bridge's global coordinate frame. In this way, the virtual pre-assembly routine provides construction crews with a complete, data-driven specification for manufacturing and installing the closure element.

4 CONCLUSIONS

This study presented a point-cloud-driven, 3D virtual-assembly method for cable-stayed-bridge closure that resolves the intrinsic shortcomings of one-dimensional match-cutting practices. By combining high-precision TLS acquisition, rigid registration of design geometry, and a particle-swarm-optimized pose-matching procedure, the workflow delivers sub-mm estimates of the closure gap and end-face attitude. Field trials conducted on the 300 m main span of the cable-stayed bridge verified the method's effectiveness.

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