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Adaptive 3D Imaging and Tolerance Analysis of Prefabricated Components for Accelerated Construction

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Abstract

Tolerance analysis of prefabricated components poses challenges to effective quality control of accelerated construction projects in urban areas. In busy urban environments, accelerated construction methods quickly assemble prefabricated components to achieve workflows that are more efficient and reduce impacts of construction on urban traffic and business. Accelerated constructions also bring challenges of "fit-up:" misalignments between components can occur due to less detailed tolerance assessments of components. Conventional tolerance checking approaches, such as manual mock-up, cannot provide detailed geometric assessments in a timely manner. This paper proposes the integration of an adaptive 3D imaging and spatial pattern analysis methods to achieve detailed and frequent "fit-up" analysis of prefabricated components. The adaptive 3D imaging methods progressively adjust imaging parameters of a laser scanner according to the geometric complexities of prefabricated components captured in data collected so far. The spatial pattern analysis methods automatically analyze deviations of prefabricated components from as-designed models to derive tolerance networks that capture relationships between tolerances of components and identify risks of misalignments.

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1. Introduction

Accelerated construction projects in urban areas can improve urban facilities with minimum impacts on traffic flows and business activities. On the other hand, these projects pose challenges to effective quality control of prefabricated components frequently used in them [1,2]. Aging urban facilities, buildings, and civil infrastructures require timely renovations and maintenances. Renovation and maintenance activities can bring undesired road closures, interruptions of urban businesses, and safety concerns in busy environments. To address these concerns, many accelerated construction methods use prefabricated components to reduce the field operation time. These methods increase the qualities of individual components, but bring challenges of field "fit-up." Fig. 1 shows two examples of such misalignments caused by "fit-up" issues. Fig. 1(a) shows that the vendors pre-framed a wall with an opening for a duct going through that wall. In the field, the lack of detailed tolerance checking resulted in accumulations of errors and caused a one-inch shift of a main duct. That shift of the main duct triggered the shifts of all ducts connected to it, including the one shown in Fig. 1(b). In this case, engineers had to pay for the time and resources for enlarging and padding the opening. Fig. 1c shows a misalignment between prefabricated concrete components installed in an Accelerated Bridge Construction (ABC) project in Iowa [3]. In this project, the remaining space for the lastly installed girder was insufficient. As a result, engineers had to bend the steel bars sticking out on sides of girders.

(a) (b) (c)

Fig. 1. Misalignments between prefabricated structural components and building systems (a) as-designed; (b) as-built; (c) bridge misalignment

The two examples described above indicate that misalignments occur at the connections between prefabricated components due to the lack of detailed monitoring of their geometries and spatial relationships. It is challenging to capture and analyze detailed geometries in such cases. Oftentimes, multiple trades are involved in the manufacturing and installation of these components. It is difficult to physically "mock-up" prefabricated components under the control of different trades for checking the constructability issues. Shape changes of these components during transportation and construction further complicate the tolerance checking. Engineers usually realize the misalignments when they almost lose control of the problem.

Within tight construction schedules, conventional surveying methods, such as using total stations, cannot capture detailed geometries needed for analyzing camber, sweep, and twists of these components [4]. Manual "mock-up" methods are tedious and thus not suitable for frequent geometric assessments; they will fail when precast components undergo substantial deformations due to various reasons (e.g., concrete shrinkage) [5]. On the other hand, recent development in the domains of 3D imaging systems [6], computer vision [7], and tolerance network [8] shows the potential of detailed, frequent, and proactive tolerance control of prefabricated components. However, two challenges remain for effective uses of these technologies in the practice. The first challenge, named as "data collection challenge," is about how to ensure fast and comprehensive 3D data collection within time limits in cluttered construction workspaces. Even experienced engineers can miss certain details needed or waste time on collecting unnecessarily high-resolution data for flat and straight geometries. The second challenge, named as "data processing challenge," is about how to derive tolerance information of prefabricated components from 3D data in an efficient and reliable manner. Even state-of-the-art 3D data processing tools require users to conduct significant amounts of manual data processing and interpretation for deriving quantitative tolerance information of objects, such as dimensional errors, camber, sweep, and twists.

This paper examines an integration of an adaptive 3D imaging mechanism and spatial pattern analysis methods to achieve detailed and frequent "fit-up" analysis of precast concrete components. As detailed below, it will provide automated supports for the 3D data collection activities (scan planning) and 3D data processing and deviation analysis activities required for tolerance checking. The authors present a case study to demonstrate how the proposed methods enable detailed tolerance analysis while reducing the time needed for geometric data collection and analysis.

2. Framework of adaptive imaging and tolerance analysis

The proposed framework of data-driven tolerance analysis involves two sets of new methods shown in **Fig. 2**: 1) the adaptive 3D imaging methods, and 2) automatic spatial pattern analysis methods. The adaptive 3D imaging mechanism enables high-quality 3D data collection within time limits of accelerated construction projects. Using data collection time as the objective function, it automatically optimizes 3D imaging parameters of a laser scanner according to the geometric complexities of components and the accuracy requirements of tolerance control. The spatial pattern analysis methods automatically classify spatial deviations of prefabricated bridge elements from as-designed models of prefabricated components. Engineers can then create tolerance networks based on deviation analysis results for analysing relationships between tolerances of individual components.

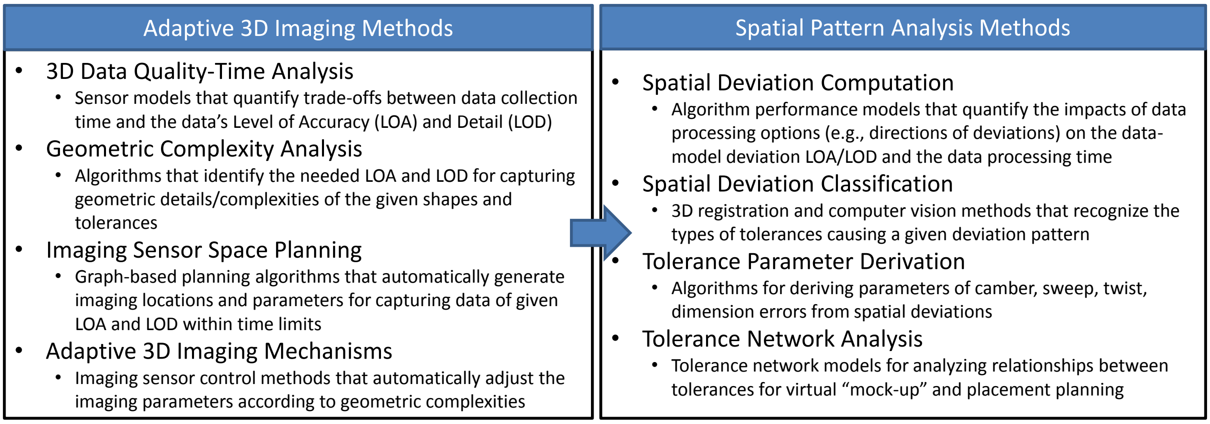


Fig. 2. Overview of the adaptive imaging and 3D-data-driven tolerance analysis framework

3. Adaptive imaging mechanisms

The adaptive imaging methods integrate a 3D imaging sensor model, geometric complexity-quality model, and sensor space planning algorithms. The fundamental idea is that the complexity of shapes of objects determines the required density of 3D data for capturing sufficient geometric details. The authors are exploring multiple methods that quantify the geometric complexities. Curvature and roughness computation from 3D surfaces are two of such methods. The curvature measures the amount by which a shape deviates from being flat [9], while the roughness measures the granularities of small features [10]. Based on curvature and roughness information computed from 3D data, a laser-scan-planning algorithm can then determine the locations and imaging parameters for capturing the geometric complexities needed for tolerance analysis. The following paragraphs use a steel I-beam shown in Fig 3, which is part of a highway bridge, to demonstrate the adaptive imaging methods.

Adaptive imaging process of this I-beam starts from an initial scanning of it in the prefabrication yard with relatively low resolution (low data densities) that takes less than 1 minute using a phase-based laser scanner. The curvature and roughness computation algorithm will then show the geometric complexities of this as-designed model of I-beam based on the point clouds. **Fig. 4** below shows the curvature and roughness visualization results of initial scans of a prefabricated steel I-beam.

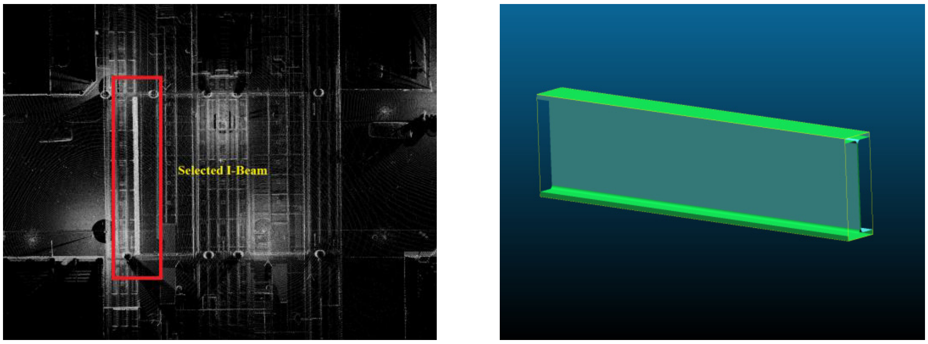
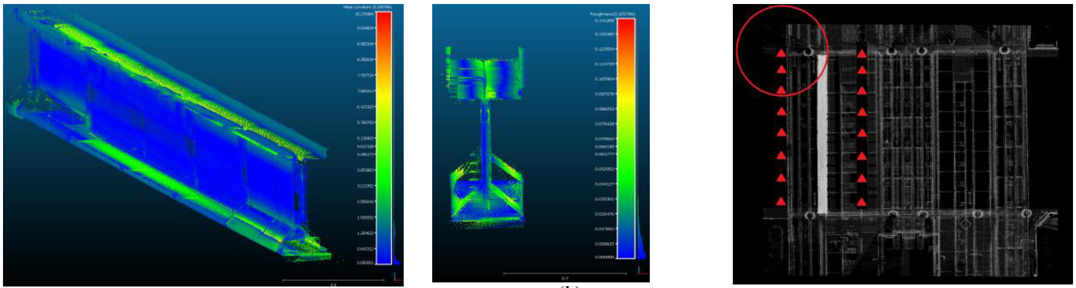


Fig 3. 3D point cloud of a steel I-beam of a bridge and its as-designed model



(a) (b) (c)

Fig. 4. Geometric complexity of I-Beams and optimal scanning locations for capturing this geometric complexity: (a) Curvature; (b) Roughness; (c) Scanning locations generated by the laser-scan planning algorithm

In Fig. 4 (a) and (b), yellow areas indicate the high curvature and roughness whereas the blue areas have lower curvature and roughness. Given the curvature and roughness results on the initial scans, the algorithm will use an analytical sensor model of laser scanners developed by the authors [11] to identify optimal scanning locations and imaging parameters (e.g., resolution, noise level). This optimization process maximizes the data densities at the parts of higher curvature and roughness values while minimizing the data collection time. Details of this optimization approach is in [12]. Optimal scanning plans for shapes with less self-occlusions (e.g., flat walls) tend to be long-distance scan with high resolutions but having less scans. On the other hand, for objects with self-occlusions, such as the I-beam in this case, optimal scanning plans would be short-distance scans with lower resolutions but there will be more scanning stations located close to each other. Fig. 4 (c) shows the optimal scanning plan for the studied I-beam. The scanning locations are roughly eight meters from the I-beam, and the spacing between the adjacent stations is roughly 3 meters. Such lower-resolution, shorter-distance, more-scans plans can achieve the same data densities as the long-distance plan, while scanning the objects from more points of views to cover occluded parts of the I-beam surface. The circle in this figure indicates the space covered by the scan located at the center of it, with sufficient details captured.

4. Spatial pattern analysis for tolerance checking

Fig. 5 shows a flow chart of the spatial pattern analysis methods that support the automatic generation of tolerance information of components and tolerance network describing how tolerances of components influence each other. The tolerance network representation is based on the one presented in [8]. The generated tolerance network comprises of the components as nodes and connections between the components as the edges. Each node and edge in the network has a number of attributes to describe the properties of objects and relationships. Examples of "node" attributes (local attributes) include length, radius, and material that define the local properties of the component, which helps in determining the errors during fabrication or during logistic operations. Attributes of edges (global attributes) could depict orientation and position for representing the installation errors. The algorithm automatically associates local attributes to every component and global attributes to the connection between components. For instance, the tolerance network representation shown in Fig. 6 has changes in lengths and radii as local attributes of nodes and change in orientation and position as global attributes associated with edges. Such tolerance network representation provides the basis to analyze tolerance error propagation and accumulation between connected components.

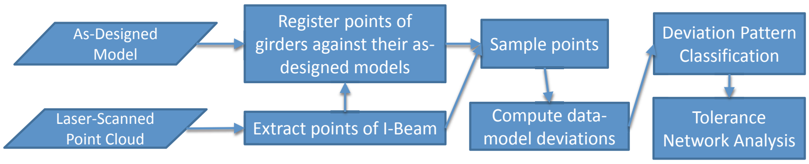


Fig. 5. Flowchart of spatial pattern analysis for tolerance checking

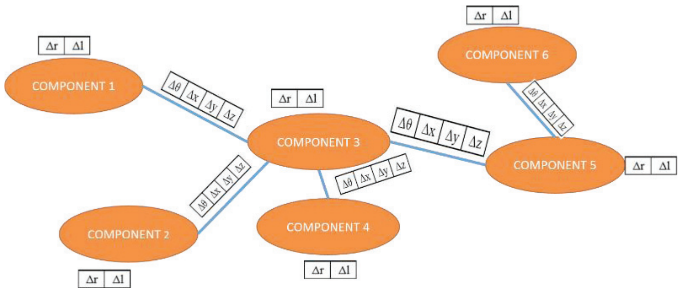


Fig. 6. Tolerance Network comprising Local and Global Attributes

5. Tolerance network generation of real building MEP components data

The collected data includes a Building Information Model (BIM) and 3D laser scanned data of a room that consists of many Mechanical and plumbing pipes connected to each other. In order to match the as-designed Building Information Model (BIM) and as-is laser scan data, the authors use the methodology developed in [13]. For testing purpose in this paper, the authors have selected nine connected prefabricated components comprising of ten cylindrical segments for generating the tolerance network shown in Fig. 7. Table 1 shows the change in both local and global attributes of the generated Tolerance Network (Fig. 8) to represent the deviations of the physical conditions from the as-designed Building Information Model. Since segments 1 and 3 are central parts of the generated network, Joint 1 that connects them is the most critical joint in this network. In this case, the authors observed that the change in local attributes is minimum and under the tolerance limitations. The change in the global attributes has propagated across the generated network. For example, the position change of Joint 1 propagated and consumed across the connections of the Segment 3 via Joint 2, Joint 8, and Joint 9 (Highlighted in Fig. 8). The change in local attributes (Length) also affected the accumulation of the change in global attributes for the segments connected to Segment 3.

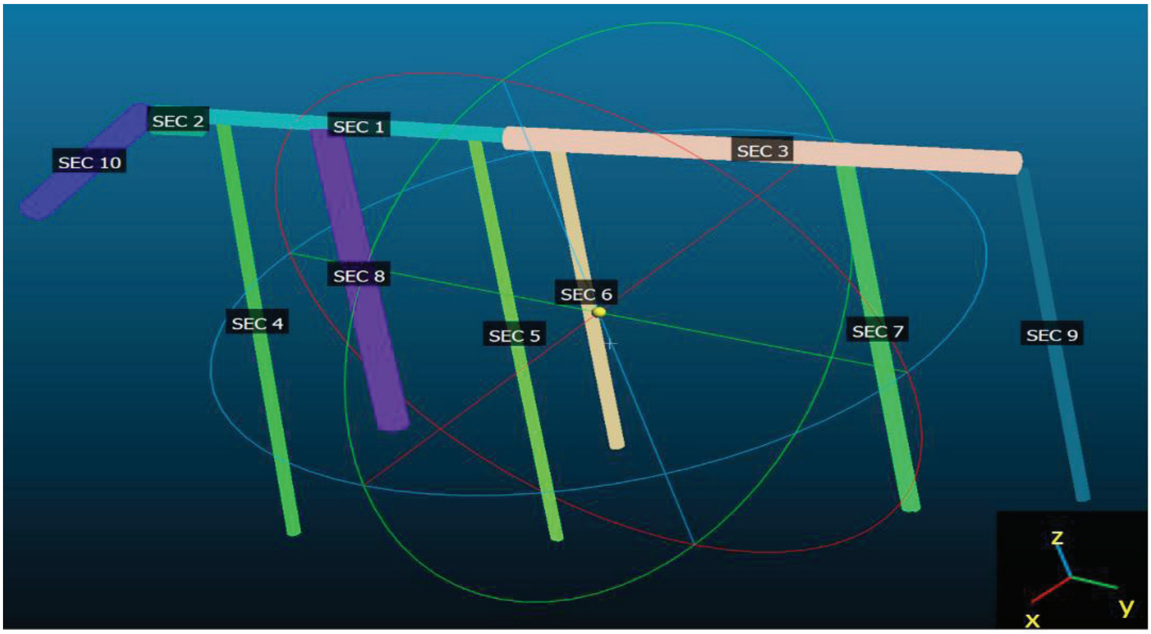


Fig. 7. Segmented As-designed BIM for network generation

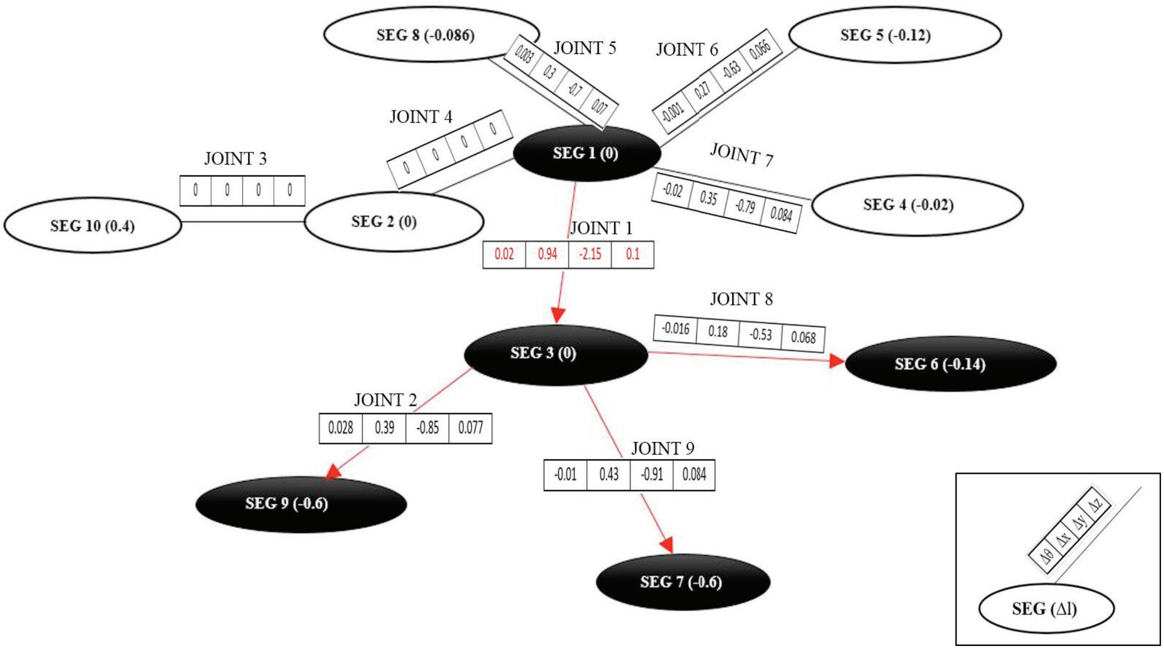


Fig. 8. Generated Tolerance Network

Table 1. Change in Attributes of the generated Tolerance Network

SEGMENT/ ATTRIBUTE	LENGTH CHANGE
SEG 1	0
SEG 2	0
SEG 3	0
SEG 4	-0.02
SEG 5	-0.12
SEG 6	-0.14
SEG 7	-0.60
SEG 8	-0.086
SEG 9	-0.60
SEG 10	0.40

JOINT/ ATTRIBUTES	ORIENTATION CHANGE (Δθ)	POSITION CHANGE (Δx, Δy, Δz)		
JOINT 1	0.02	0.94	-2.15	0.1
JOINT 2	0.028	0.39	-0.85	0.077
JOINT 3	0	0	0	0
JOINT 4	0	0	0	0
JOINT 5	0.003	0.3	-0.7	0.07
JOINT 6	-0.001	0.27	-0.63	0.066
JOINT 7	-0.02	0.35	-0.79	0.084
JOINT 8	-0.016	0.18	-0.53	0.068
JOINT 9	-0.01	0.43	-0.91	0.084

6. Conclusion

This paper presents a computational framework that enables more efficient and effective tolerance analysis of prefabricated components using 3D imaging technologies. The adaptive imaging methods can assist engineers to adjust data collection locations and imaging parameters according to geometric complexities of prefabricated components in low-resolution data collected by the laser scanner. Object parts of higher curvature and roughness will be the targets of detailed data collection. Such progressive data collection planning can reduce data collection time while ensuring required data densities for the tolerance checking. Given high-quality 3D data, spatial pattern analysis will then enable automatic derivation of tolerance network of building components to support automated data-driven tolerance checking. The authors observed propagations of fabrication and installation errors of prefabricated components through generating the tolerance network based on 3D imagery data and as-designed Building Information Models.

In future, the authors would like to explore along two directions. First, the authors plan to examine various methods for automatically deriving areas on job sites requiring detailed and frequent 3D data collection, such as areas having higher risks of accidents based on site simulation studies, not limited to geometric complexity analysis. Second, the authors plan to investigate automated error propagation and accumulation analysis using the laws governing fluid dynamics. Such study would facilitate engineers to make accurate decision without leading to cascading effects. Classifying the tolerance deviations of the components, understanding the correlations between them would help in achieving adaptive redistribution and reliable construction quality checking.

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