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Dimensional accuracy and structural performance assessment of spatial structure components using 3D laser scanning

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ABSTRACT

Spatial structures have been constructed around the world, and their components have become increasingly complicated. Quality inspection is primarily manually performed and is a labor intensive approach which is prone to error. Developments in 3D laser scanning offer great opportunities to improve the precision and efficiency of quality control operations. This paper presents a new approach for assessing the dimensional accuracy and structural performance of spatial structure elements using 3D laser scanning. The proposed approach establishes a holistic assessment framework by considering the evaluation parameters, optimized scanning strategy, and data processing. A data processing method is developed to automatically calculate and compare the difference between the reverse model and design model based on point cloud processing, reverse modeling, and finite element analysis. A new algorithm is proposed to automatically extract the point cloud boundaries, and it is capable of streamlining the generation of reverse models. The assessment criteria and error control for the framework are quantitatively described in a systematic manner. The proposed approach is tested and demonstrated through an actual project. The results show that using 3D laser scanning for the quality control of spatial structure elements is suitable and validate that applicability of the proposed approach compared to traditional measurement methods.

1. Introduction

Spatial structures have played an increasingly important role in the construction industry in recent decades due to their diverse architectural forms and adequate structural performance. Countries worldwide have made significant investments in the development of spatial structures to improve the efficiency and effectiveness of construction. The traditional forms of spatial structures are mainly regular surfaces or combinations of regular surfaces, such as spherical, cylindrical, and saddle surfaces. With economic and technological developments, more attention has been given to the aesthetics of architecture. For instance, free-form structures with rich architectural expression have become increasingly favored by architects [1–3], and many complex spatial structures have been built around the world.

Consequently, the complexity of structural elements has significantly increased because most of the corresponding elements have twisted forms in space [4,5]. The manufacturing processes of such components requires high quality, and on-site construction requires high precision. However, errors cannot be completely avoided. The errors associated with spatial structure elements may arise from the dimensional errors of raw materials, welding deformation, transport extrusion, and other factors. To assess structural performance and avoid conflicts among building shells, the structural elements must be inspected before the outside building shells are installed.

The conventional methods of assessing the dimensional accuracy and structural performance of spatial structure elements are mainly manual and rely on one-dimensional (1D) approximate linear measurements [6,7]. Although conventional methods are convenient for geometrically simple structures, they are time consuming and imprecise for complex structures. Especially for flexure-torsion members, conventional detection approaches will not work because the spatial performance of these elements cannot be precisely evaluated. Therefore, a new assessment approach for spatial structure elements is urgently needed.

In this paper, a novel approach is proposed using 3D laser scanning to overcome the limitations of the available methods [6–11]. Notably, 3D laser scanning techniques can provide an accurate surface of the tested elements consisting of point clouds, which can reflect the actual spatial performance of the element. In addition, point clouds can be transformed into actual models and compared with design models through reverse modeling. In this study, the entire assessment framework and the point cloud processing method are proposed. Moreover,

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the applicability of the methodology is demonstrated based on a case study.

After the introductory section, the content is organized as follows. In Section 2, we present a review of the existing methods for quality inspection of spatial structures and laser scanning-based applications. The assessment framework for a spatial structure element and the methodology, which is applied to process point clouds obtained from laser scanning, are described in Sections 3 and 4. In Section 5, a case study is presented, and the results are evaluated to determine the effectiveness and applicability of the proposed assessment procedure. Section 6 summarizes the main conclusion of this paper.

2. Research background

2.1. Existing approaches for the quality assessment of spatial structure elements

Traditionally, inspections of spatial structure elements are manually performed. There are two main inspection approaches: (1) by direct sketches based on visual observations or using a steel tape, the distance between the two ends of an element is usually simply described, as shown in Fig. 1(a), and (2) using a total station, the coordinates of several feature points of an element are recorded, as shown in Fig. 1(b). For instance, after the coordinates of both ends of a strut are determined, the perpendicularity can be used to estimate the additional stress associated with this strut [12]. However, such manual inspections are time consuming and laborious, and more importantly, they lack sufficient accuracy.

2.2. 3D laser scanning-based approaches

Laser scanning technology can rapidly record an object surface with high accuracy. Therefore, this technology has become increasingly important in the high-precision 3D detection of structures and has been applied in many fields [6,13–17].

2.2.1. Dimensional quality assessment

From a broad perspective, Bosche and Guenet [18] presented an approach to demonstrate the value of the integration for surface flatness control. Kim et al. [19,20] proposed an approach for dimensional and surface quality assessment of precast concrete elements using building information modeling (BIM) and 3D laser scanning technology. Lee and Park [21] proposed algorithms that led to the automation of laser scanner-based inspection operations. Moreover, Nuttens et al. [22] presented a clear process flow and interpretable deliverables during two recent tunneling projects in Belgium with submillimeter accuracy.

2.2.2. 3D model generation from point clouds

With a focus on 3D model generation from point clouds, Varady et al. [23] reviewed the process of the reverse engineering of shapes, including the most important algorithmic steps and various reconstruction strategies. Laefer and Truong-Hong [24] proposed a method to identify structural steel members from a point cloud and to generate the corresponding geometry in a BIM-compatible format. Conde-Carnero et al. [25] proposed a methodology to convert point clouds to finite element analysis (FEA) models using several commercial software products. Walsh et al. [9] developed an object detection method based on a predefined library that used a generic description of the object, and they demonstrated the applicability of the method. Bosche et al. [26] presented a unified approach for more robust automated comparison of as-built and as-planned cylindrical MEP (Mechanical, Electrical and Plumbing) works. Anton et al. [27] analyzed the 3D modeling accuracy associated with the creation of historical building information models based on a three-stage semi-automatic approach.

2.2.3. Structural assessment

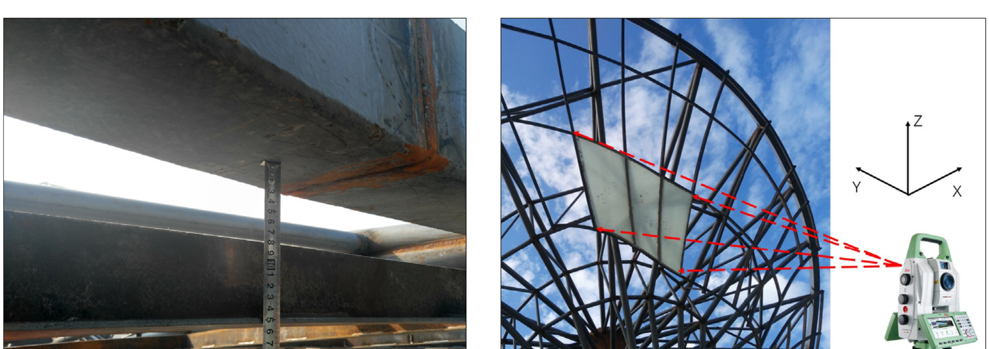
In addition, many literatures have also made positive contributions to the application of laser scanning in the structural analysis. Lubowiecka et al. [28] presented an approach that integrated laser scanning, ground penetrating radar (GPR) and finite element analysis in the documentation of a medieval masonry bridge. Jahanshahi et al. [29,30] proposed a vision-based method for accurate quantification of microcracks. Castellazzi et al. [31] aimed at the generation of finite element models with a reduced amount of time and ready to be used with structural analysis.

These practices demonstrated the high-efficiency and feasibility of 3D laser scanning in quality detection and provided various assessment methods for different objects. However, for space-bending elements, especially special-shaped elements, the exploration of relevant detection methods has been limited. In addition, an effective pathway from point clouds to dimensional detection and further into structural analysis is still lacking. Therefore, a holistic assessment system that can automatically analyze spatial structure elements is needed.

3. Assessment framework of spatial structure elements

3.1. Overview of the assessment framework

An overview of the proposed approach for precisely assessing the dimensional accuracy and structural performance of spatial structure elements is described in this section. The flowchart of the proposed assessment framework is presented in Fig. 2. The detection parameters and scanning strategy, which will be used in the following assessment, should be clarified first. Sequentially, the point cloud data are processed to obtain the parameter results. Finally, the assessment results are given, and the reliability of the results is verified. The details of the assessment procedure are developed in this section, and the data



(a) (b)

Fig. 1. Existing approaches: (1) using a steel tape or (2) acquiring coordinates with a total station.