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Computationally efficient change analysis of piece-wise cylindrical building elements for proactive project control

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ABSTRACT

The designs of large-scale building systems, such as Mechanical, Electrical, and Plumbing (MEP) systems, undergo spatial changes during design-construction coordination, and as a result, their as-built conditions deviate, in some cases significantly, from their as-designed conditions. Construction engineers need to detect and analyze the differences between as-designed and as-built conditions of building systems promptly for responsive change management. Existing data-model comparison approaches either cannot correctly detect changed objects packed in small spaces, or cannot handle the computational complexity of comparing detailed as-designed and as-built geometries of MEP systems that contain hundreds or even thousands of elements (e.g., ducts). This paper presents a computationally efficient spatial-change-detection approach that reliably compares as-designed Building Information Models (BIMs) and 3D as-built models derived from laser scan data. It integrates nearest neighbor searching and relational graph based matching approaches to achieve computationally efficient change detection and management. A case study using data collected from a campus building was conducted to compare the new change detection approach proposed in this paper against the state-of-the-art change detection techniques. The results indicate that the proposed approach is capable of making more precise data-model comparisons in a computationally efficient manner compared to existing data-model comparison techniques.

1. Introduction

Frequent changes in construction projects pose challenges to design-construction collaboration due to cascading interactions between design changes and field adjustments [1]. Incomplete design information, improper field operations, and unexpected site conditions may result in deviations between as-designed and as-built conditions of building components, which may lead to misalignments between components [2–4]. Also, such changes may propagate along networks of building elements (e.g. ductworks), and cause cascading effects that are difficult to track. The propagation of design-built deviations among building elements usually requires a significant amount of change coordination efforts among multiple stakeholders. Improper change management could cause reworks, wastes, delays during construction while increasing construction costs [5]. Furthermore, poor change coordination may also create interruptions in decision-making processes during Operations and Maintenance (O & M) phase. O & M planning can become challenging if detailed changes between as-built and as-designed conditions and information about how spatial changes propagate along the spatial and temporal domains are missing [4]. Construction engineers, therefore, have to analyze design changes and field adjustments causing design-built differences and find ways to control the impacts of such changes on project performance [6,7].

Recent technological advancements, such as Building Information Modeling (BIM), enabled construction engineers and managers to coordinate design and construction activities of multiple trades involved in a project [8]. Commercial BIM software facilitates the visualization of building elements including Mechanical, Electrical, and Plumbing (MEP) systems for coordination purposes so that potential clashes among building elements can be resolved virtually before constructability problems occur on site [9]. Some BIM tools support the comparison of multiple versions of as-designed models to detect changes between versions and record design change histories for change management [10]. However, manual updates of as-designed BIM could be error-prone and may miss certain spatial changes occurring in the field. As a result, only using design-oriented BIM tools could hardly track differences between as-designed and as-built conditions [11].

Several researchers explored the potential of using three-dimensional (3D) imaging technologies, namely 3D laser scanning and

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photogrammetry coupled with computer vision, for change analysis between as-designed and as-built conditions. 3D laser scanning is an emerging technology that can capture very accurate as-built geometries promptly [12,13]. Data produced by 3D laser scanners is in the form of dense 3D point clouds. Such point clouds can be used to detect differences between as-designed models and as-built conditions [2]. However, associating objects from the as-designed model with points in point clouds in an efficient and reliable manner is challenging, especially when spatial changes occur [14]. Tang et al. identified the challenges associated with detecting and classifying spatial changes during design and construction processes [14]. That study concluded that a robust spatial change detection and classification approach would enable reliable automatic diagnosis of the propagative effects of changes that cause reworks and construction quality problems. Recent studies of the authors explored the application of relational graphs to match and compare objects from 3D as-designed models with the objects in the corresponding 3D as-built model accurately [2,4,15], which has significant advantages over data-model comparison tools that are available in commercial 3D data processing and reverse engineering environments, such as InnovMetric Polyworks [16]. However, comparing relational graphs generated from as-designed models and 3D laser scan data of large-scale building systems (e.g., hundreds of inter-connected ductworks) involves computational complexity that grows exponentially with the number of building elements [15].

This paper presents a novel approach that combines multiple algorithms to achieve a reliable and computationally efficient comparison of as-designed model and as-built models derived from laser scan data. This approach first calculates the distances between as-designed model objects and their corresponding geometries in the as-built model using the nearest neighbor algorithm, which derives a “data-model deviation map.” The algorithm then uses the deviation map to isolate parts of the as-designed model that contain deviations larger than a threshold and applies reliable but computationally expensive relational graph matching to those isolated parts. The algorithm finally utilize the connectivity and spatial relationship between building elements to correct mismatches produced in the first step of “nearest neighbor matching,” making sure that parts that have small deviations are all correct matches. This last step is necessary to avoid cases when certain as-designed and as-built objects that are not corresponding but happen to occupy the same space and have similar geometries. In brief, the developed approach leverages the computational efficiency of the nearest neighbor searching while narrowing the scope of executing computationally expensive relational graph matching to isolated model parts that contain significant changes. The objective is to achieve reliable data-model matching while maintaining computational efficiency.

The following section (Section 2) first provides a comprehensive review of challenges associated with the current design – construction change analysis and management methodologies. Section 3 details the proposed novel approach for efficient and reliable change detection. Section 4 uses the as-designed model and laser scan data of a large-scale ductwork of an educational building to validate the efficiency and reliability of the proposed approach. Sections 5 and 6 discuss research findings, draw conclusions, summarize advantages and drawbacks of the proposed approach, and recommend future research directions.

2. Background

Construction industry adopted various technologies such as BIM and 3D imaging for managing changes in construction projects. The first subsection below reviews the literature on change management approaches employed in current design and construction practice. The change management during the design phase handles changes between multiple versions of as-designed models, while the change management during the construction phase focuses on comparing as-designed and as-built models. Section 2.2 discusses the advantages as well as the limitations of the widely adopted change detection paradigm – nearest neighbor searching, which forms the basis of many previously published change detection methods in the domain of construction engineering and management.

2.1. Change management in the current design and construction practice

Design changes have various impacts on the quality and performance of a construction project [1]. Poor communication among different trades and poor documentation practices lead to design changes and rework during construction [3]. In current practice, design changes are documented as “Change Orders” as per the procedures defined by the American Institute of Architects (AIA) [17,18]. Architects follow these guidelines and manually log all the design change orders, which is time-consuming and error-prone.

BIM technology addresses the difficulties associated with design change coordination by enabling synchronization of multiple trade design models in a central BIM for clash detection and coordination [8]. Langroodi & Staub-French [19] conducted a case study to exploit the benefits of using BIM for design change management of a fast-track project. Akinci and Boukamp [20] concluded that BIM can document different design alterations, but could hardly address the propagative impacts of changes that collectively influence the construction quality, cost, and productivity. Also, BIM tools mainly focus on design change coordination, while engineers are required to update as-designed BIM manually according to the as-built conditions to analyze the impact of field changes on the project performance. This practice is tedious and error-prone.

Previous studies focused on automated modeling of as-built pipelines from laser scan data for construction quality assessment and monitoring purposes [21–23]. Construction project managers would use these as-built models to investigate any dimensional deviations between the individual objects of the as-built and as-designed models. Several studies investigated the integrated use of 3D imaging technologies and BIM for detecting and analyzing spatial changes that occur in the field. Tang et al. reviewed a broad range of algorithms and techniques that are used for the recognition and reconstruction of building elements from 3D laser scan data for as-built modeling [12]. Based on this review, Xiong et al. [24] developed methods that automatically create semantically rich BIM from 3D laser scan data using voxel representation to make the as-designed and as-built BIM comparison more efficient. Similar concepts inspired a study that developed an approach for automated spatial change analysis of linear building elements [15]. Bosché developed a robust point matching method for as-built dimension calculation and control of 3D CAD model objects recognized in laser scans [25]. Based on this work, Turkan et al. [26] developed an automated progress monitoring system that combines 4D BIM and 3D laser scan data for change detection and management. Nahangi and Haas [27] developed an automated deviation detection approach for pipe spools based on Scan-to-BIM registration. This study employed an automated registration step for quantifying the deviations in the defective parts of the pipe spool assemblies. Bosché et al. [28] coupled Scan-versus-BIM, and Scan-to-BIM approaches to track and diagnose changes of densely packed cylindrical MEP (Mechanical, Electrical, and Plumbing) elements.

The majority of the studies described above utilizes nearest-neighbor searching algorithms for detecting spatial deviations and changes between as-designed and as-built conditions and thus inherit the limitations of this algorithm. In many cases, especially when several similar objects packed in small spaces (e.g., several ducts packed in a mechanical room), the change detection results of nearest neighbor searching may contain mismatches that associate data points with the wrong objects in the as-designed model [15]. As a result, the change analysis and progress monitoring results would be misleading. The following sub-section introduce the nearest searching algorithm and its limitations in more detail.