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Semantic as-built 3D modeling of structural elements of buildings based on local concavity and convexity

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ABSTRACT

The aim of this study is to propose a method for generating as-built BIMs from laser-scan data obtained during the construction phase, particularly during ongoing structural works. The proposed method consists of three steps: region-of-interest detection to distinguish the 3D points that are part of the structural elements to be modeled, scene segmentation to partition the 3D points into meaningful parts comprising different types of elements (e.g., floors, columns, walls, girders, beams, and slabs) using local concave and convex properties between structural elements, and volumetric representation. The proposed method was tested in field experiments by acquiring and processing laser-scan data from construction sites. The performance of the proposed method was evaluated by quantitatively measuring how accurately each of the structural elements was recognized as its functional semantics. Overall, 139 elements of the 141 structural elements (99%) in the two construction sites combined were recognized and modeled according to their actual functional semantics. As the experimental results imply, the proposed method can be used for as-built BIMs without any prior information from as-planned models.

1. Introduction

Interest has been growing regarding how best to model and represent building facilities in as-is conditions. For project management purposes, the composing building elements need to be represented in volume-enclosing and solid shapes that have three-dimensional (3D) forms at the individual object level; they also need to have their own information regarding functional semantics in as-built building information models (or BIMs) [1–7]. In BIMs, building elements consist of structural and nonstructural elements. Structural elements comprise floors, columns, walls, girders, beams, slabs, and foundations; nonstructural elements include architectural elements (e.g., freestanding walls, canopies, interior partitions, stairways, ceilings, and exterior walls), mechanical, electrical, and plumbing (MEP) elements (e.g., electrical equipment, piping, ductwork, and mechanical equipment); and other finishes (e.g., windows and doors). All building elements are networked with neighboring elements to perform their respective functions. For example, two or more columns can be connected with a girder for support. In BIMs, the 3D shapes of such elements, their functional semantics, and the connectivity relations between them need to be described. Accordingly, when generating as-built BIMs, it is necessary to recognize each of the semantic elements to be modeled and to identify the connectivity relations among the elements [8]. Additionally, a building is constructed by following a plan that includes all work activities during the construction phase. As that phase progresses, most of the elements (particularly the structural elements) are covered by other objects, such as architectural elements and finishes, which are installed late in the process. For this reason, it is necessary to generate and update as-built BIMs during or after each major construction activity (e.g., the structural, MEP, architectural, and finish steps) to ensure that the BIMs include all of the composing building elements.

Although designers first create the 3D models of building facilities in an office environment, discrepancies (in terms of, for example, dimension, location, orientation, and shape) certainly exist between as-built and as-planned models [9–11]. Such discrepancies can become wider as the construction phase progresses due to manual layouts and on-site guesswork. Thus, as-planned BIMs can become inaccurate or even obsolete if considerable revisions are not made to reflect the construction process. In spite of the existence of early design in the form of 3D models, such a revision process—which should incorporate the design changes and construction errors that take place during the construction phase—is intricate. To close this gap, it is necessary to generate as-built BIMs based on real-world information at every stage during construction [12,13].

Nowadays, a highly accurate laser-scanning survey can be utilized

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to capture real-world information for generating as-built BIMs of building facilities that are under construction. Performing a laser-scanning survey during major construction activities (whether ongoing or completed) allows us to generate and update as-built 3D BIMs based on highly accurate, as-built point clouds. To generate as-built BIMs from such accurate and dense point clouds, it is necessary to recognize all the semantic building elements and to separate them from one another. Few studies have attempted to solve this problem. Previous studies can be largely divided into those that considered an as-planned model during the recognition process and those that did not. Some researchers (e.g., [14–19]) have attempted to model structural elements by aligning as-built data with computer-aided design (CAD) models, recognizing individual elements, and then retrieving 3D elements from as-planned models or a 3D CAD database. However, the as-planned model does not always depict the same elements that are present at the scene during construction; thus, the recognition of individual elements ends up being incomplete. Such discrepancies between the as-built and as-planned conditions may be due to (human) construction errors or changes made in the field regarding constructability issues. Other studies (e.g., [3,20–22,4,23–29]) have recognized that, during the occupancy phase, the exposed parts of the structural and architectural elements can be recognized and/or modeled without an as-planned model or a 3D CAD database. However, as the basis of these methods is planar patch extraction, these methods require additional processes to identify the nonplanar volumetric elements or those that consist of several planes, including columns, walls, girders, and beams [2,30,31]. In summary, to our knowledge, there are limited methods available to generate an as-built 3D BIM during the construction phase without an as-planned model.

The ultimate goal of this study is to develop a method for generating and updating as-built BIMs during or after each major construction activity, including structural, MEP, architectural, and finish work; this method could serve the purposes of project management. To realize this goal, this study proposes a method for generating as-built BIMs from laser-scan data obtained during the construction phase; this method would be especially useful for structural work.

2. Related works

Several research studies have been conducted to attempt to automate the generation of 3D as-built models of structural elements of buildings. Some studies (e.g., [14–19]) have proposed methods to recognize and model structural elements from as-built data by utilizing as-planned models or a 3D CAD database.

In the methods proposed by Bosché et al. [14], Bosché [15], and Turkan et al. [19], 3D point clouds are registered with an as-planned model in the same coordinate system with an iterative closest point. Once the 3D CAD models of structural elements and 3D point clouds are registered, the as-built objects are recognized. Then, the structural elements are modeled by retrieving matched 3D CAD models. Son and Kim [16] proposed methods to recognize and model structural elements from as-built data by utilizing a 3D CAD database. In their method, the data processing is initiated by extracting 3D point cloud that corresponds to structural elements from the as-built data based on those elements' color features. They also modeled the as-built objects by aligning the as-built data with the CAD model, recognizing individual elements, and retrieving 3D elements from the as-planned model or from a 3D CAD database. Kim et al. [18] proposed a method to recognize and model structural elements from as-built data by utilizing a four-dimensional (4D) BIM. Once the as-built data is aligned with the as-planned model and matched to the information in the BIM, the construction sequence—defined as the sequence-of-activity execution specified in the BIM—is examined to help identify the inaccurate aspects of the as-built status. Then, the topological relationships among the structural elements—defined as the connectivity between elements, as specified in the BIM—are examined. The as-built status-revision phase results in an accurate assessment of the as-built status of the structural elements.

These methods mainly rely on point-recognition metrics that identify correspondences between the as-built data and either the as-planned model or a 3D CAD database to recognize individual elements and retrieve 3D elements from the as-planned model or a 3D CAD database. For this reason, these methods can cause recognition errors when discrepancies—in terms of dimension, location, orientation, or shape—are observed between as-built conditions and as-planned models. Although a recent study by Bosché et al. [9,10] tackled this issue by integrating the scan-versus-BIM and scan-to-BIM approaches in the as-built modeling of MEP work, this integrated method also primarily depends on the as-planned model.

Other researchers (e.g., [3,20–22,4,23–29]) have recognized that, the exposed parts of structural and architectural elements can be recognized and/or modeled without an as-planned model or a 3D CAD database. This can be accomplished through the extraction of planar patches, the segmentation and classification of patches, and the creation of a model that includes all the building elements that have planar surfaces. Pu and Vosselman [3] proposed a method to generate building-façade models from 3D point cloud. Façade elements (e.g., walls and roofs) are distinguished as features. To recognize these features from segmented 3D point cloud, information about the features' sizes, positions, orientations, and topologies is used. Then, a polygon is created for each feature—using least-squares fitting, convex-hull fitting, or concave-polygon fitting, according to the size of each feature. Information from the created polygons is used to hypothesize about the occluded parts. Finally, a building-façade model is generated from the polygons and the hypothesized parts. Truong-Hong et al. [21,22] proposed an approach to generate 3D façade models from 3D point cloud. Their approach is capable of detecting the building façade's boundary points, features, and determining the openings. For this purpose, the flying-voxel method is used to determine whether each point belongs to the building's façade. The approach is then used to generate surface models of the building façade using an octree representation.

Xiong et al. [4] proposed an approach to generate 3D indoor building models from 3D point cloud. Their method is capable of identifying and modeling the main structural elements of an indoor environment (e.g., walls, floors, ceilings, windows, and doorways), even in the presence of clutter and occlusion. Their proposed approach begins with the extraction of planar patches from a voxelized 3D point cloud; the features of various types of surfaces and the contextual relationships between them are then identified, and each patch is labeled as one of various types of main structural elements. After that, openings such as windows and doorways are located via visibility reasoning. Next, a learning algorithm is used to estimate the shape of these window and doorway openings, and occluded surface regions are filled in using a 3D inpainting algorithm.

As the basis of these methods is the process of planar patch extraction, each of the elements—such as walls, doors, and roofs in an outdoor environment or walls, floors, ceilings, windows, and doorways in an indoor environment—is represented in the form of a planar (that is, non-volumetric) surface. To be more specific, in previous methods (e.g., [29]), the objects are not in the form of 3D, solid, volume-enclosing shapes; instead, each element is represented by only a single surface or by a few separate surfaces. For example, these methods represent a wall as a planar surface, but the wall would best be represented as a single, volumetric object with multiple surfaces and adjacency relationships between it and other elements in its BIM [32]. Thus, these methods require additional processes so that nonplanar volumetric elements or those that consist of several planes—such as columns, walls, girders, and beams—can be recognized [2,30,31]. For example, a column can be recognized by using additional processes to identify the various planes that comprise the column; it is then necessary to combine them into a unified entity. Some researchers (e.g., Xiao and Furukawa [33]; Stambler and Huber [34]) have proposed a method