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As-built data acquisition and its use in production monitoring and automated layout of civil infrastructure: A survey

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ABSTRACT

The collection and analysis of data on the three-dimensional (3D) as-built status of large-scale civil infrastructure – whether under construction, newly put into service, or in operation – has been receiving increasing attention on the part of researchers and practitioners in the civil engineering field. Such collection and analysis of data is essential for the active monitoring of production during the construction phase of a project and for the automatic 3D layout of built assets during their service lives. This review outlines recent research efforts in this field and technological developments that aim to facilitate the analysis of 3D data acquired from as-built civil infrastructure and applications of such data, not only to the construction process per se but also to facility management – in particular, to production monitoring and automated layout. This review also considers prospects for improvement and addresses challenges that can be expected in future research and development. It is hoped that the suggestions and recommendations made in this review will serve as a basis for future work and as motivation for ongoing research and development.

1. Introduction

Advancements in on-site spatial survey technologies (e.g., photo/video-grammetry and terrestrial laser scanning) enable more efficient acquisition of 3D data on as-built civil infrastructure (hereinafter referred to as "as-built data") than is possible with traditional manual techniques. In this review, the term *as-built* refers to either the actual state of an entire facility or one of its constituent components at the completion of construction, or to the actual state of a built asset at any time during its life cycle, particularly during its service life. Three-dimensional as-built data acquired from civil infrastructure have been used to establish geometric properties of entire facilities and their constituent components. More recently, such data have come to be regarded as a tool to be utilized for managerial purposes at various points in the life cycle of a project: during construction, upon completion of construction, and during operational and maintenance phases relevant to the civil engineering field.

For purposes of on-site dimensional quality control, progress tracking, and inspection, one particularly important application of as-built data in the construction phase is production monitoring, which entails making comparisons of the actual ("as-built") state of a project with the "as-designed" state defined in the contractual agreement. Examples of research studies in this area include proactive on-site tracking of the physical progress of construction activities by comparing 3D as-built data acquired on the site of a facility under construction with the design information embedded in the building information model (BIM) (e.g., [1–11]).

There are several reasons why it is so important – indeed, vital – for researchers and practitioners to develop new methods and technologies for use in production monitoring. For starters, the design documents may not provide complete details of a planned facility, leaving some aspects thereof to the owner and the contractor to decide later. Because of such delayed decisions, it can be difficult if not impossible to adequately record the as-built condition of an entire facility or of one of its constituent components within the as-built documentation. Such situations are particularly common in the case of mechanical, electrical, and plumbing (MEP) systems that are not fully designed (e.g., those whose characteristics are specified in only rudimentary form, such as via line sketches) [9,10]. In addition, it is sometimes difficult to adequately track and record (within the as-built documentation) changes based on conscious decisions that are made during construction and hence could yield a final product that deviates from the as-designed state. Finally, it can be even more difficult to adequately track and record (in the as-built documentation) deviations that are more subtle and are not the results of conscious decisions (e.g., deviations due to poor workmanship).

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Another important aspect of the construction, operation, and maintenance phases of civil infrastructure is automated layout. The Oxford English Dictionary defines *layout* as "the way in which the parts of something are arranged or laid out." The Collins English Dictionary defines *layout*, in its technical sense, as "a drawing showing the relative disposition of parts in a machine, etc." In this review, the term *automated layout* is used to mean the process of automatically determining geometric properties (dimensions, shape, and 3D position (location and orientation)) and other semantic (real-world) attributes of individual components of a structure, as well as the relationships between them, from 3D as-built data.

Automated layout is used for documentation purposes, such as in the preparation of a contractual agreement that must be delivered by the contractor to the owner – that is, a package that contains all the pertinent as-built information, particularly CAD drawings. Automated layout is also used for purposes of facility management, to record and update the status of the built assets. Some studies have focused on transforming 3D as-built data acquired from a facility into 3D structured or object representations, such as CAD models, in order to better illustrate the as-built conditions (e.g., [12–16]). Such representations or models can then be used as the basis for making managerial decisions (e.g., on repairs and maintenance).

Recording of information on the as-built status of individual components of a facility is needed, because the as-designed state, such as CAD drawings or early component selections made by the design team, may not correspond to the infrastructure actually produced. This could be due to contractors (for the initial construction or for subsequent add-ons or modifications) either not adequately and fully capturing the state of the facility as built, not building precisely to design, or handing over the design documentation without fully communicating that the asset was not built as designed. Regardless of the reason for discrepancies between the as-built state and the as-designed state, an aggravating factor is the owner's potential lack of control over the as-built information. Even if an accurate 3D as-built layout of the facility is produced – whether after the construction phase, in the case of new construction; or after a renovation, upgrade, or remodeling of part/all of the facility; or after replacement of one or more of its constituent components – the original as-built layout must be modified on a timely basis to reflect and update the state of the facility.

Situations such as the ones described above have created a need for methods and technologies that enable the robust, efficient, and cost-effective acquisition of as-built data on demand, and subsequent processes for the extraction of the valuable as-built information by construction professionals and facility managers. For this reason, methods for acquisition of such data through on-site surveys and the extraction of valuable information – to be used for production monitoring during the construction phase, and for automated layout during the construction, operational, and maintenance phases – have been investigated by researchers and practitioners in the civil engineering field.

This review provides an extensive survey of the technological advancements that have made it possible to extract and process valuable as-built information for purposes of production monitoring and automated layout. Existing research efforts in this area are outlined in Section 2, and efforts by practitioners are discussed in Section 3. Areas in which further developments are needed are summarized in Section 4.

2. Review of existing research

The acquisition of as-built data is especially useful in the civil engineering field, where it aids in control/verification of the quality of civil infrastructure – via analysis of deviations between as-built and as-designed structures – and in monitoring of progress on a project. Another practical application is the production of as-built drawings, where it facilitates the determination and documentation of as-built layout. Two types of non-contact spatial survey technology have recently made it possible to efficiently acquire as-built data: those based on photo/video-grammetry (image-based technologies) and those based on terrestrial laser scanning (range-based technologies) [17]. With either of these types of survey technology, as-built data can be acquired by capturing the shape and structure (i.e., spatial coordinates) of an object in point-cloud format [18]. This section presents an extensive review of recent research into the analysis and application of collected 3D data on as-built civil infrastructure for purposes of production monitoring and automated layout.

2.1. Production monitoring

Acquisition of 3D as-built data via photo/video-grammetry and terrestrial laser-scan surveys has led to automated quality assessment of construction projects, with a focus on dimensional compliance of structural components [19], tracking of progress on individual structural components [1–8,11], dimensional compliance of MEP systems [20], tracking of progress on MEP systems [9,10], and inspection tasks, especially for surface flatness [21].

2.1.1. Dimensional quality control of structural framing work

Bosché [19] proposed a method for automated recognition of structural components that are designed in 3D CAD from 3D point clouds obtained at the building construction site. A point-to-point matching approach is used, and registration is performed with an iterative closest point (ICP) algorithm. Once the registration between 3D CAD models of structural components and 3D point clouds is completed, a similar ICP-based registration algorithm is used to calculate the poses of models of structural components. These as-built poses are then used to automatically control the compliance of the project with respect to the corresponding dimensional tolerances (see Fig. 1). Specifically, the differences between the as-built and as-designed dimensions (within and between objects) are calculated and compared to their corresponding tolerances defined in the project specifications, which may be specific to the project or refer to industry standards such as MNL 135-00 [22] and AISC 303-05 [23].

2.1.2. Progress tracking for structural framing work

2.1.2.1. Permanent structural work. A decade ago, Shih and Wang [24], Akinci et al. [25], and Shih and Huang [26] proposed methods for quantifying as-built structural progress by comparing differences between the actual work done on the construction site and the original construction schedule. For this purpose, they proposed the use of a 3D point cloud acquired by terrestrial laser scanning and a 4D (3D + time) building information model that represents the original building design and construction schedule. Although the differences were identified manually and visually under this scan-versus-BIM framework at the time of the study, research has enabled this process of construction progress tracking to advance to the point where it can now be automated.

Bosché and Haas [1] and Bosché et al. [2] proposed methods for automated recognition of structural components that are designed in 3D CAD from 3D point clouds. In their earlier work, the as-planned 3D CAD model was converted to a point cloud model. Using point-recognition metrics, correspondences between the as-planned and as-built models were identified, and the progress on the project was able to be ascertained. In the study by Bosché et al. [2], they introduced an object-surface recognition metric that achieves high precision and recall on structural steel buildings.