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.

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Keywords: As-Built, Automated Layout, Civil Infrastructure, Photo/Video-grammetry, Production Monitoring, Terrestrial Laser Scanning

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).

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].

Fig. 1.

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.

Golparvar-Fard et al. [3,27] proposed a method for calculating the locations and orientations of construction site images from the images themselves as well as by 3D as-built data acquisition based on photogrammetry. With this method, 3D as-built data can be superimposed on as-planned models. Also, as-built progress can be quantified by registering construction site images in a virtual as-planned environment and analyzing the registered images—and then using the as-planned 4D model as a baseline for progress tracking. The results of comparisons of as-built and as-planned progress are represented in a 4D augmented reality (D4AR) environment.

In a later study, Golparvar-Fard et al. [5] proposed a method of progress measurement that compares construction site images acquired daily with a 4D BIM. In this method, an updated as-built point cloud is generated in 4D (3D + time) from the latest images by use of structure-from-motion, multiview stereo, and voxel coloring and labeling algorithms. Then an industry foundation class (IFC)-based BIM is registered with the updated as-built point cloud. Next, a Bayesian probabilistic model-based machine-learning method is used to measure physical progress on the project, which can be represented in D4AR, as illustrated in Fig. 2.

Fig. 2.

Still another method of progress monitoring was devised by Son and Kim [4], who used an automated 3D method of recognition and modeling of structural components that employs color and a 3D point cloud acquired from a stereo vision system. The data processing first relies on color features to effectively extract information on structural components by employing color invariance, 2D object segmentation, median filtering, and flood fill operation. That information is then utilized to extract the 3D coordinates of each color feature. The final step in the proposed method is the use of the resulting 3D point cloud to generate matching 3D as-built CAD models that have been converted to STL format, which enables project participants to automatically assess project progress.

Turkan et al. [6] developed an automated 4D object-oriented progress-tracking system to efficiently update the construction schedule through the use of a 3D CAD model, schedule information found in the original plans for the project, and 3D point clouds acquired via terrestrial laser-scan surveys. In their system, 3D point clouds are registered with a 4D as-planned model in the same coordinate system, in order to extract useful information on the progress of a project. Once registered, progress measurement and schedule updating is automatically performed by recognition of as-built objects. In a later study, Turkan et al. [8], they proposed a 4D-model recognition-driven system for automated tracking of progress on steel-reinforced concrete structures and steel structures that transforms objects to their earned values.

Kim et al. [7] proposed a method of progress measurement that uses a 4D BIM in concert with a 3D point cloud obtained by terrestrial laser scanning. The method comprises three phases: alignment of the as-built data with the as-planned model, matching of the as-built data to information in the BIM, and revision of the as-built status. To help identify aspects of the as-built status that are inaccurate, the construction sequence—defined as the sequence-of-activity execution specified in the BIM—is first examined. Then the topological relationships among the structural components—defined as the connectivity between components which is 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 components, demonstrating that this methodology can be used to correctly measure construction progress (see Fig. 3).

Fig. 3.

2.1.2.2. Secondary and temporary work

Turkan et al. [11] developed a method that can be used for tracking of progress on secondary (rebar) and temporary (formwork, scaffolding, and shoring) objects employed in structural concrete work. Previous research had shown that scan-versus-BIM object-recognition systems, which fuse 3D point clouds acquired by photogrammetry or terrestrial laser scanning with a 4D BIM, provide valuable information for tracking of construction work. However, the potential of these systems had been demonstrated for tracking the progress of permanent structures only. The experimental results achieved by Turkan et al. [11] show that it is feasible to recognize secondary and temporary objects in 3D point clouds—and to do so with fairly high accuracy—via either of these two novel fusion techniques (see Fig. 4). However, superior results could be achieved by using additional cues such as color and 3D edge information.

Fig. 4.

2.1.3. Dimensional Quality Control of MEP Work

Nahangi and Haas [20] proposed a method for monitoring and assessment of fabricated pipe spools using an automated scan-to-BIM registration procedure in which defects are detected through a neighborhood-based ICP algorithm (see Fig. 5). They focused on industrial construction facilities, and targeted assemblies of pipe spool in particular. This method can be employed for the automatic and continual monitoring of such assemblies throughout fabrication, assembly, and erection, thereby enabling timely detection and characterization of deviations.

Fig. 5.

2.1.4. Progress Tracking for MEP Work

Bosché et al. [9,l0] proposed a system that integrates scan-versus-BIM and scan-to-BIM approaches for tracking of the built status of MEP work. This system, which is capable of recognizing and identifying objects that are not built at their as-planned locations (see Fig. 6), enables automated quality control and can even detect discrepancies between the as-built and as-planned states of pipes, conduits, and ductwork. Such discrepancies are due to changes made in the field that either go unnoticed (human error) or are not reflected in the 3D model.

Fig. 6.

2.1.5. Automated Inspection and Quality Assurance

Recently, Bosché and Guenet [21] proposed a method that demonstrates the value of integration of techniques for surface-flatness control. The method employed the scan-versus-BIM principle of Bosché and Haas [1] to segment a 3D point cloud acquired on a construction site, by matching each point to the corresponding object in the BIM. Using two different standard flatness-control techniques, Straightedge and F-Numbers, to measure compliance with the designed tolerances, they applied their method to a separate 3D point cloud for each floor. They found the performance of the method to be superior to traditional measurement methods in terms of both quality and efficiency, thereby validating the usefulness of as-built data acquired by terrestrial laser scanning for purposes of standard dimensional control.

2.2. Automated Layout

2.2.1. MEP Systems in Industrial Facilities and Buildings

Because of the increasing demand for automated layout of large as-built 3D pipelines in recent years, several methods for reconstruction of 3D pipelines have been proposed. A 3D layout of an as-built pipeline at an existing plant provides detailed information on each of its distinct elements. Such a model comprises straight pipes, elbows, reducers, and tee pipes with specific diameters, lengths, orientations, and locations. Therefore, it can be used effectively during the ongoing operation, maintenance, and retrofitting of the plant facility [28,29,14]. For example, piping components are periodically renewed during preventive maintenance, and unplanned emergency repairs or replacements may be required after accidents or failures. When a single pipeline (in a network of pipelines) requires maintenance, repairs, and/or replacements, the 3D as-built pipeline layout model allows the facility manager to easily locate the pipeline and ensure that it is correctly repaired and maintained [30]. Moreover, older pipes may need to be retrofitted—or new ones may need to be added—to increase production that stems from capacity expansion and/or process integration [31], which sometimes requires the paths of existing pipelines to be rerouted. In such cases, piping plans (comprising proposed diameters, lengths, and slopes, among others) should be reviewed in conjunction with the 3D as-built environment [32]. Furthermore, the location of the equipment and the surrounding environment should be taken into account.

The existing research studies on reconstruction of 3D pipelines range from the development of semi-automated methods (e.g., [33,28,34,31,35]) to fully automated ones (e.g., [12–16]). All of these are based on more efficient survey techniques, such as photogrammetry and laser scanning, than are traditional manual surveys.

2.2.1.1. Semi-automated methods

In the case of semi-automated methods (e.g., [33,28,34,31,35]), the reconstruction of 3D pipelines is conducted in an interactive way between the user and the computer. In most cases, the user manually selects the desired portions of pipelines (straight pipes, elbows, tees, etc.) to be modeled. This process involves manual selection of vertices, centerlines, edges, or regions of the desired portions of the pipelines. Next, these manually selected features are used as input for automatic estimation of the poses of the desired portions in 3D space and for the calculation of parameters, such as their radii and lengths, that are needed to reconstruct the desired portions by computer.

Veldhuis and Vosselman [28], Navab and Appel [34], and Reisner-Kollmann et al. [35] proposed semi-automated methods based on photogrammetry, which enables the reconstruction of as-built pipelines from multiple digital images acquired from industrial facilities such as chemical processing plants, oil platforms, nuclear installations, and power plants. Navab and Appel [34] studied only the reconstruction of straight-pipe portions of pipelines. Veldhuis and Vosselman [28] proposed a method that is capable of reconstructing elbows, but they tested their method only on straight-pipe portions. Reisner-Kollmann et al. [35] proposed a method that allows for the reconstruction of entire pipelines, but in the form of tubes without boundaries between the different types of pipe (straight pipes, elbows, tees, etc.).

The semi-automated methods based on photogrammetry require correspondences among vertices, centerlines, edges, or regions across multiple images in order to reconstruct the desired portions in 3D. Therefore, the user has to manually measure the edges of every straight pipe [28] or the centerline of every pipeline [35] in a series of digital images. For example, in the computation for the reconstruction process proposed by Veldhuis and Vosselman [28], every straight pipe has to be measured manually in at least four images, the minimum requirement for reconstruction of a straight pipe being that two points on the edges of a straight pipe be present in two images. In an experiment on reconstruction of 16 straight pipes, Veldhuis and Vosselman [28] actually used eight images and manually measured 256 edges (16 edges for each pipe). They recommended using even larger numbers of images and measured edges of each straight pipe in order to improve the quality of reconstruction.

In the semi-automated methods based on photogrammetry, there is a primary assumption that a series of digital images is already pre-calibrated, hence these methods rely highly on pre-calibration. For this calibration, markers have to be attached in advance to each of the desired portions of the pipelines to be modeled [34,35] (see Fig. 7). In addition, both intrinsic and extrinsic parameters of the cameras must be provided. These tasks, which include the identification of correspondences of the desired portions across a number of images and pre-calibration that requires extensive manual intervention, are not only time-consuming for the user but also become nearly impossible for entangled pipelines and for enormous facilities that include a large number of pipelines.

Fig. 7.

Because of improvements in laser scanning, Johnson et al. [33] and Masuda and Tanaka [31] proposed semi-automated methods that allow for the reconstruction of as-built pipelines from a 3D point cloud acquired by terrestrial laser scanning on the site of an industrial plant. Compared with photogrammetry, laser scanning provides an explicit, dense 3D point cloud by directly and quickly measuring the 3D positions and shapes of as-built pipelines [14]. Recent advances in laser scanning have made it possible to automatically capture large-scale 3D point clouds from a broad range of areas [31].

In the method proposed by Johnson et al. [33], the user manually selects and draws rectangular regions around the portions of the pipelines to be modeled (straight pipes, elbows, tees, etc.) in a series of range images acquired from many different viewpoints. Next, smooth surface-mesh models of those regions are generated, and they are registered to a single, seamless surface-mesh model. In the mesh-generation process, the user specifies the amount of scene data to be processed, and the range image is sub-sampled for mesh generation. The registered surface-mesh models for the regions of interest can be recognized once CAD drawings have been provided for each type of pipe (straight pipes, elbows, tees, etc.). However, if the desired portions differ too much from the given CAD drawings, they cannot be recognized and modeled. Finally, after the regions of interest are identified, each pipe is modeled by manually rotating and orienting it so that its actual position and orientation correspond with those of some pipe in the given CAD drawings.

In the study by Masuda and Tanaka [31], smooth mesh models are first generated automatically from a 3D point cloud. Then the portions that are missing in the mesh models—because of the limited number of viewpoints or partial occlusion by a large number of objects—are manually compensated for, based on the reflected images. These reflected images have the form of unit spheres, which can be converted to two types of images: a perspective image for users and a rectangular image via Mercator projection for purposes of computation. The user intuitively selects a seed region (such as one which is included in a desired portion of a perspective image), and then the corresponding pixels in the rectangular image are detected automatically. At that point, the desired portions are modeled by fitting a surface to vertices in the selected seed region. Then when the user specifies the locations and sizes of the desired portions according to the standards, the adjacent vertices that like on that surface are searched via the region-growing method (see Fig. 8).

Fig. 8.

A great deal of user input is involved in the semi-automated layout process. With most methods based on either photogrammetry or laser scanning, such input is available only if all of the straight pipes or pipelines are visible (i.e., nearly free of occlusion by other objects). Another inherent drawback of these methods is that the reconstruction is error-prone if the user makes a mistake or the user input is not sufficiently accurate [35]. Furthermore, methods based on photogrammetry have other, more limitations: Their use is limited to portions of straight pipes or to entire pipelines that can be modeled as tubes without boundaries between different types of pipe. Therefore, it is difficult to use them for reconstruction of an entire 3D pipeline, since most pipelines are composed of a series of straight pipes connected to one another by elbows, tees, etc.

Although the aforementioned techniques based on laser scanning represent a major step forward in terms of their capacity for reconstruction of an entire 3D pipeline, they still entail a large number of manual processes. From a practical point of view, recognizing each type of pipe from a noisy, incomplete, and enormous 3D point cloud that includes a large number of pipelines becomes nearly impossible if it has to be done in a semi-automated way with manual intervention.

2.2.1.2. Fully automated methods

Several research studies (e.g., [12–16]), have investigated the possibility of automatic modeling of 3D as-built pipelines. These studies have all yielded similar advancements in terms of automatic performance.

Bosché [12] proposed an automated method that enables reconstruction of as-built straight and curved pipes from a 3D point cloud acquired from pipe spools that surround buildings (see Fig. 9). Bosché's method iteratively fits and matches all cylindrical pipes by adopting the method proposed by Kwon [36]. Once that is done, two or more adjacent straight pipes are analyzed to compare their relative positions and orientations in an effort to determine how they are likely to be connected. In this way, the positions of the elbows are inferred, and the positions of some of the straight pipes that are connected to other straight pipes or elbows are corrected accordingly.

Fig. 9.

Rabbani et al. [13] proposed an automated method that enables reconstruction of as-built cylindrical pipes from a 3D point cloud acquired at an industrial plant (see Fig. 10). In this method, segmentation of the point cloud is performed using a smoothness constraint based on a combination of surface-normal similarity and spatial connectivity. This segmentation is followed by an object-recognition stage based on a variation of the 3D Hough transform, which requires a 5D Hough space for detection of the orientations of cylindrical objects and estimation of their radii and positions in the point clouds. Then cylindrical 3D-object models are fitted using models from a catalogue of commonly found CAD objects as templates.

Fig. 10.

Kawashima et al. [14] also proposed an automated method for reconstruction of as-built pipelines from a 3D point cloud acquired at an industrial plant. In their method, the entire 3D pipeline is reconstructed by automatically recognizing the type of each pipe (such as straight, elbow, or tee) and the connections between pipes. First, points on straight pipes are extracted by eigenvalue analysis of the point clouds and the surface-normal vectors. Then the radii, positions, and axes of the straight pipes are calculated using the point clouds. At that point, the connection relationships among the extracted straight pipes are determined by checking the relative positions and orientations of their axes. Based on these connection relationships, other types of pipes, such as elbows and tees, are modeled.

Lee et al. [15] proposed an automated method that enables reconstruction of as-built pipelines composed of straight pipes, elbows, and tee pipes from a 3D point cloud. In their study, Voronoi diagrams are used to generate skeleton candidates for individual pipelines from the point cloud. Then extraction of skeletons from the skeleton candidates is performed using topological thinning. The extracted skeletons are segmented into their individual components, and a set of parameters for each component is calculated (see Fig. 11).

Fig. 11.

Ahmed et al. [16] proposed a method based on the Hough transform and the judicious use of domain constraints that can automatically find, recognize, and reconstruct 3D pipes from a 3D point cloud. The core algorithm utilizes the Hough transform's efficacy in detecting parametric shapes in noisy data by applying it to projections of orthogonal slices to grow cylindrical pipe shapes within a 3D point cloud. They considered that most of the pipes, conduits, and ducts are built orthogonal to one another and along the main axes of a building. In this way, searching in planes perpendicular to these axes for standard reference pipe diameters reduces the problem from three to two dimensions (see Fig. 12).

Fig. 12.

The previous methods are limited to parts of an entire 3D pipeline, for example, straight pipes, elbows, and tees in the most recent study by Lee et al. [15]. Although the study by Kawashima et al. [14] attempted to achieve an improvement in terms of the completeness of the modeled 3D pipeline layout, only 55% of the individual pipes (other than the straight pipes) were accurately modeled from their actual pipe forms. In addition, in the studies by Kawashima et al. [14] and Lee et al. [15], the detection of as-built pipelines from a 3D point cloud was performed manually before the proposed reconstruction process was initiated.

Previous attempts to address this problem range from the development of semi-automated methods to assist users in a tedious manual reconstruction process to the development of fully automated methods that eliminate any user involvement. The results of these efforts have shown that the repetitive, tedious, and even trivial tasks typically performed in the manual 3D reconstruction of as-built pipelines can be eliminated by using automated approaches. However, there is still a need for an effective, fully automated 3D reconstruction method that can model an entire pipeline, irrespective of the types of its constituent parts. Specifically, as-built pipelines, though generally cylindrical, present a challenge to automatic detection because of the variety of types (shapes) and diameters of pipes and the arbitrariness of their poses. Additionally, the incompleteness and unstructured nature of a point cloud complicates automation [16,37]. For automatic performance, algorithms must be improved to the point of being able to handle point clouds that are somewhat less than complete and to predict, extrapolate, semantically relate, or otherwise represent the parts that are occluded or missing [16].

2.2.2. Buildings

Jung et al. [38] proposed a method for modeling of a semantically rich 3D indoor building layout from a 3D point cloud acquired by terrestrial laser scanning. Their method, which is a semi-automatic approach that accounts for the high degree of complexity of indoor environments, comprises three main steps: segmentation for plane extraction, refinement for removal of noisy points, and boundary tracing for outline extraction. After these steps are performed, the resulting 3D indoor building models are used in conjunction with the points that were not processed in the three main steps to create manual models. With the extracted boundary lines as guides, each object and its relationship each other can easily be identified and modeled (see Fig. 13).

Fig. 13.

3. Commercial and State-of-the-Art Tools

Currently, modeling which is done to represent the existing state of an as-built pipeline or the 3D layout of an as-built building is mostly performed manually—in an interactive manner—by the user. Especially, 3D layout of as-built pipelines from 3D point clouds has been extensively investigated, and several commercially available software programs have been developed to asssit the current manual process of 3D layout.

Most providers of laser-scanning systems (e.g., Leica Geosystems and Trimble) have developed software that enables the 3D layout of as-built pipelines from 3D point clouds. For example, the latest version of Leica Cyclone (version 8.1) by Leica Geosystems provides a user interface for 3D layout of as-built pipelines that includes functions for tasks such as automatic pipe finding, region growing from selected 3D points for cylindrical objects, cylinder fitting, and generation of models from the selected 3D point clouds. With this software, models of objects of various geometric types pertinent to the 3D layout of as-built pipelines, for example, cylinder, elbow, reducing elbow, cone, torus, reducer (eccentric and concentric), and pipe tee, can be created by a semi-automatic layout process.

Chunmei et al. [39] and Qiusheng et al. [40] used Cyclone (version not specified) by Leica Geosystems to model the 3D layout of as-built pipelines from a 3D point cloud. In the study by Chunmei et al. [39], the noise-removal function was used to eliminate some noise prior to the modeling. Then users manually segmented the complicated pipeline network into individual pipelines and used the cylinder-fitting function to model the layout of the various segments, which could contain both straight and bent parts. Chunmei et al. [39] remarked that with their method, prior knowledge (design data) is required if some parts of the as-built pipelines are missing in the acquired 3D point clouds on account of self-occlusion or occlusion by other objects. In the study by Qiusheng et al. [40], users manually selected 3D point clouds corresponding to the individual pipelines in a network and used the region-growing function to determine the boundary of each pipeline. After the boundaries were found, the cylinder-fitting function was used to model the pipeline layout.

Trimble RealWorks provides the EasyPipe tool for modeling of pipeline layout, which extracts 3D points for cylindrical objects and fits cylinders to them. Then models of the elbows can be aligned and connected to the models of the cylindrical pipes.

In addition to Cyclone, Leica Geosystems has released several plug-in tools for 3D layout of as-built pipelines from 3D point clouds: Leica CloudWorx for AutoCAD Pro 5.0, Leica CloudWorx for Revit version 1.0.2, and Leica CloudWorx for MicroStation 4.0. By using these plug-in tools, it is now possible to import and process the 3D point clouds inside AutoCAD, Revit, and MicroStation. There are several functions that are especially useful for 3D layout of as-built pipelines, such as one that generates cylinders based on least-squares fitting from the selected 3D point clouds and one that connects cylinders with elbows.

The leading 3D CAD vendors (Autodesk, Bentley, Aveva, and Intergraph) have also developed software that enables the 3D layout of as-built pipelines from 3D point clouds. One example of this is AutoCAD Plant 3D, which can be used with Kubit's PointSense Plant add-in for AutoCAD (see Fig. 14(a)). PointSense Plant by Kubit provides several functions for pattern recognition that can identify pipelines from 3D point clouds. Then users manually model the layout of as-built pipelines by fitting CAD objects to the segmented 3D point clouds.

SmartPlant 3D by Intergraph has functionality similar to that of the combination of AutoCAD Plant 3D and Kubit's PointSense Plant add-in for AutoCAD (see Fig. 14(b)). SmartPlant 3D's fitting function automatically calculates the best fit for cylinders from 3D point clouds that have been selected manually. In addition, the cylinders can be placed manually, and then the software calculates the orientation and extent of the cylinders by evaluating the point clouds.

Fig. 14.

The aforementioned programs are user-friendly tools for the 3D layout of as-built pipelines, as they provide several functions for manipulation of 3D point clouds acquired by laser scanners and have the capability to create and modify pipeline models [39]. However, large 3D point clouds are not easily managed and processed, so they need to be divided into several smaller parts. Recently, Autodesk ReCap provided an efficient mechanism for managing such large 3D point clouds by using different file formats (e.g., RCS and RCP).

The recently developed EdgeWise Plant™ (version 4.0) provides a function that automatically detects the straight sections of a pipeline and fits cylinders to them (see Fig. 15). This software is a powerful engine that can handle large 3D point clouds. However, its use is limited to only the straight sections of a pipeline, whereas an entire pipeline can include other forms of pipe. Hence, significant user intervention is required, both to identify pipes that are not straight and to uncover any undetected straight pipes that need to be modeled.

Fig. 15.

The aforementioned reconstruction programs are in common use but are not fully automated, as they rely on substantial operator input/intervention to model the 3D layout of an as-built pipeline [44]. Although some programs provide semi-automated functions such as region growing, the user still has to mark certain portions of pipeline manually, to indicate that they are to be modeled [45,46]. To exploit the potential advantages of obtaining a 3D layout of an as-built pipeline, it is necessary to accurately measure the dimensions of installed pipelines and efficiently model them [35]. However, marking portions of individual pipelines in an enormous and complicated set of 3D point clouds is very time consuming and labor intensive. Furthermore, it is difficult to identify individual pipelines from a 3D point cloud, because pipelines of various radii, lengths, and orientations can be installed in complex configurations. In a study conducted by Fumarola and Poelman [47], it took 15 days to model the layout of 2,602 objects (planes and cylinders) by a semi-automatic layout process. In a study by Sanders [48] of a Chevron installation that was being revamped, 40% of the total cost of modeling of the layout was spent on data-processing labor [48].

4. Conclusions and Recommendations

4.1. Summary and Discussion

Over the last decade, efficient acquisition of 3D as-built data from civil infrastructure based on photo/video-grammetry and terrestrial laser-scan surveys has been a matter of increasing interest in the civil engineering field. Researchers and practitioners alike have engaged in efforts to develop semi- or fully automatic data processing methods and technologies to assist in and support the tasks of production monitoring and facility management.

These efforts demonstrated that such tasks can be automated to some degree. In particular, several methods for dimensional compliance or progress tracking have been demonstrated to be applicable to work on permanent structural components, such as frames of buildings [1–3,19,4,27,5–8], brick façades [27], and MEP systems [9,10,20]. Recently, the study by Turkan et al. [11] demonstrated the applicability of their method to secondary components (e.g., rebar) and temporary components (e.g., formwork, scaffolding, and shoring) of steel-reinforced concrete structures. Such advancements demonstrate the feasibility of using automated modeling to track the accuracy of progress on a construction site.

In addition, several methods have been proposed for automated layout of built assets. Most of these efforts have targeted as-built pipelines in MEP systems in industrial facilities and buildings [12–16] and in indoor structures in low-rise buildings [38]. These research efforts have improved the level of automation that can be applied in the layout of certain parts of an entire facility and have expanded the types of parts that can be modeled in an automated manner.

The reviews in Sections 2 and 3 show the extent and emergence of survey technologies that aim to improve and enhance the accuracy and ease of acquiring and communicating as-built information. While these technologies have already been widely studied by architecture, engineering, construction, and facility management (AEC/FM) researchers and practitioners, further developments in the performance of such technologies are needed—particularly in regard to their robustness across different kinds of environments—for them to become widely accepted and used in the civil engineering field. Some of the existing challenges and the likelihood that future research and development will succeed in meeting them are discussed in what follows.

First, combinations of different surveying technologies are expected to overcome the drawbacks of individual methods. The so-called hybrid approach combines data acquired from photo/video-grammetry and terrestrial laser-scan surveys, which has the potential for enhancing the fidelity of the measurements and hence the overall accuracy of the 3D reconstruction. Few research studies have used the hybrid approach for acquisition of as-built data on civil infrastructure (e.g., [49–52]). However, the feasibility of this approach in applications such as production monitoring and automated layout merits investigation.

Second, the data acquired by photogrammetry and terrestrial laser-scan surveys can be combined with data obtained by other identification and localization technologies, including radio frequency identification (RFID) [53–55], ultra-wide band [56,57], near-field communication [58,59], wireless local/personal area network [60], and information and communication technologies such as building information modeling and mobile technologies [61–63]. For example, Valero et al. [63] proposed combining terrestrial laser scanning with RFID for the purpose of constructing basic 3D semantic models of inhabited interiors. As is well known, the segmentation and identification of objects from a 3D point cloud acquired by terrestrial laser scanning is a challenging task. In their study, Valero et al. [63] applied RFID tags to various objects and found that they served as a valuable aid in the identification and positioning of those items. Therefore, the fusion of photogrammetry and terrestrial laser-scan surveys with data acquired by other identification and localization technologies holds promise as a source of improvements in the applications discussed above.

Third, the structural components of buildings that have been targeted for automation of production monitoring thus far are frames of buildings, brick façades, and MEP systems, but automation of production monitoring of other components (substructure, foundation, external envelope, roof, internal complementary elements, finishes, and so on) needs to be demonstrated as well. In addition, despite the fact that significant progress has been made in the automation of data acquisition and processing, further progress is needed, particularly for the complete automated layout of built assets. Advancements in this area should be extended to even larger classes of structures and their constituent parts, and may benefit from further development of as-built data acquisition methods.

Fourth, in order for production monitoring and automated layout methods and technologies to become established practice in the civil engineering field, there must be significant improvements in the methods used for processing of the huge amounts of 3D as-built data acquired from civil infrastructure. Most civil infrastructure is large scale and complex, hence data must be acquired at dozens or hundreds of locations, and the data are usually vast, noisy, and unstructured. Thus research is needed in order to realize advancements in the speed of data acquisition, the accuracy of the models generated, and the degree of detail provided in the models.

Fifth, recent work has shown that recognition techniques based on scan-versus-BIM frameworks indeed enable the recognition of 3D objects in 3D as-built data acquired by terrestrial laser scanning, leading to progress in areas such as dimensional quality control [2,19,4,6–8,20]. Similar approaches use 3D as-built data reconstructed through photogrammetry-based surveys [3,27,5]. However, the authors argue that methods based on scan-versus-BIM frameworks have not yet achieved a high level of effectiveness, and that the use of scan-to-BIM frameworks for generation of as-built 3D BIM models from 3D point clouds could contribute to overcoming this limitation.

Finally, the practicality of the methods and technologies used in the generation of models of 3D as-built data should be ensured. As-built data acquired from different types of civil infrastructure may have different characteristics in terms of complexity, noise level, and completeness. Hence, it is imperative that such differences in characteristics be taken into account—and that, if need be, the methods and technologies used for specific civil engineering projects be tailored to those projects.

4.2. Concluding Remarks and Future Directions

Academic research and industrial efforts in automation of analyzing of 3D as-built data have laid the cornerstone for future research and development, especially in terms of advancements in the efficiency of construction tasks such as production monitoring and automated layout. It is expected that such tasks can be more fully automated through academia–industry collaboration. It is also expected that future efforts will contribute to the realization of the automation of additional construction tasks, such as dismantling, renovation, and revision of existing civil infrastructure.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2013R1A1A2A10058175).

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