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

As-Built Data Acquisition and Its Use for Production Monitoring and Automated Layout in Infrastructure: A Survey

The collection and analysis of the three-dimensional (3D) status of large-scale civil infrastructure that is either under construction, newly put into in service, or currently in operation are now receiving focused attention from researchers in the civil engineering field. It is not only effective and essential for the active management of construction projects, but also for facility management during their service life. Advancements in spatial data collection technologies (e.g., laser scanning and photogrammetry) enable the collecting 3D status information of civil infrastructure in the form of dense point clouds efficiently and accurately. Recent research has been devoted to developing approaches for the application of collected 3D status information for construction and facility management purposes. Examples of these studies present on-site tracking of the physical progress of construction activities in a proactive manner by comparing collected 3D status information of new facilities under construction with the designed state-of-objects information that is embedded in the building information model (BIM). From inception onward, some of these studies have been interested in transforming collected 3D status information into structured or object representations, such as a CAD model, in order to understand the as-built condition. Then, the produced 3D infrastructure model relates to applications in which the represented condition of the built environment is used as a basis for making managerial decisions (e.g., regarding repair and maintenance).

This paper will survey the recent studies that have been conducted in order to develop the approaches for analyzing and utilizing collected 3D status information of civil infrastructure for construction and facility management purposes. This paper will serve as an exposition of the methods and a review of alternative methods and applications about this theme. The following list of potential topics is provided to stimulate ideas for manuscripts. This paper concerned with—but not restricted to—this list, but the final submission will provide relevant and practical insights framed by these research questions:

- Why is production monitoring and automated layout an interesting topic in civil infrastructure?

- What are the issues that are explored in the recent studies? What kinds of methods have been

developed to analyze the collected 3D dense point clouds that are potentially usable in civil infrastructure applications?

- Why is production monitoring and automated layout useful? What kinds of applications have been explored in the past? Are there any promising applications?
- What suggestions are there for possible future research directions?

1. Introduction

Demand has been growing for three-dimensional (3D) reconstruction of as-built pipelines that occupy large areas within operating plants. A three-dimensional (3D) model of an as-built pipeline at an existing plant provides detailed information concerning 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 operations, maintenance, and retrofitting of the plant facility (Veldhuis and Vosselman 1998; Ermes 2000; Kawashima et al. 2012). For example, piping components are periodically renewed during preventive maintenance; however, unplanned, emergency repairs or replacements may also be required after accidents or failures. When a single pipeline among a network of pipelines requires maintenance, repairs, and/or replacements, the 3D as-built pipeline model allows the facility manager to easily locate the pipeline and ensure that it is correctly fixed and maintained (Tangelder et al. 1999). Moreover, existing plant facilities often need to retrofit old pipes or add new ones to increase their production during capacity expansion and/or process integration (Masuda and Tanaka 2010), 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 correspondence with the 3D as-built environment (Chapman et al. 2004). Additionally, the location of the equipment and the surrounding environment should be considered.

2. Current Problems and Requirements

The as-built 3D pipeline reconstruction process consists of measurement of the plant facility, identification of the pipelines, and generation of the 3D pipeline model. The traditional method for generating an as-built 3D pipeline model involves the use of theodolites to measure the

dimensions of the installed pipelines (Veldhuis and Vosselman 1998). Ideally, an operator should measure the dimensions of the entire pipeline installation. This would be prohibitively expensive, however, particularly for large and complex facilities, as such measurements entail considerable manual work and time (Chapman et al. 2004). Moreover, an operator who measures the dimensions of installed pipelines in an industrial plant over extended periods of time may be exposed to an unacceptable level of risk because of the hazardous nature of the environment of such a plant (Veldhuis and Vosselman 1998). As a result, the traditional method of measuring pipelines has been restricted to localized use (Chapman et al. 2004).

Although the 3D as-built pipeline model is useful, the current practice is quite a labor-intensive process with difficulties in recording the as-built condition of the pipeline. Even the manual reconstruction process becomes tedious when a large number of pipelines in plant facilities are involved, most of which constituting complicated pipeline networks. In addition, such a laborious process poses challenges in updating the model for changes in the as-built condition, leading to a discrepancy between the original model created when the plant was first built and its current as-built condition.

With recent developments in laser-scanning technology, problems with measuring the dimensions of pipelines have been rectified. However, the laser-scan data contains hundreds of thousands or even millions of points, which leads to increased computing requests. In addition, unfortunately, the point cloud data acquired from the plant facility by the laser scanning survey can be noisy arising from sensor errors, the presence of enormous outliers, the non-uniform sampling due to varying surface reflections and can be incomplete because of missing points due to feature occlusion. Moreover, the point cloud data include regional oversampling arising from simple surface geometries and scanner positions. For this reason, identification of the pipelines from large and complex sets of laser-scan data and 3D pipeline model generation remains a challenging problem. In this chapter, the data characteristics are discussed.

The acquired laser-scan data contain laser scanning characteristics due to surface reflective properties (Sareen et al. 2012). The 3D points from the pipeline surfaces can have different level of noise due to their different signal-to-noise ratio depending on the reflectance of the pipeline surface (Wehr and Lohr 1999; Dias et al. 2006). For this reason, sometimes, no laser points are reflected from the cylindrical surface itself (Jochem et al. 2011). In addition, the pipelines are

cylindrical shaped objects and have curved surface. In this case, the acquired laser-scan data can have outliers due to oblique insertion of the laser scanning characteristics (Nakamura et al. 1999).

The as-built pipelines in the plant facilities are complicated and form the confused pipe net (Chunmei et al. 2009). They are crossed over each other, and even they are surrounded by many different types of objects, equipment, and structures. In addition, the as-built pipelines are passing through several floor levels in order to link between the pieces of equipment. The complexity of geometry results in the incompleteness of the laser-scan data (Johnson et al. 1997; Rabbani et al. 2006; Masuda and Tanaka 2010).

Especially for large objects and spaces, the regions with missing data may become significant because huge occlusions can exist between neighboring structures or discontinuous surfaces. Incompleteness occurs when cylindrical surfaces are occluded by other non-transparent objects towards the laser beam, so some parts can be missing (Sonka et al. 1999; Kim et al. 2003; Jochem et al. 2011). Incompleteness of the data results in the major problem in 3D reconstruction. The occluded regions can be effectively captured by placing the scanner in front of these regions and thereby reducing incident angle and corresponding surface occlusions.

In order to acquire the laser-scan data from the plant facility as complete as possible, it requires a number of scans to be performed from different viewpoints to deal with self-occlusion problems (Martins et al. 2005; Dias et al. 2006). In other words, it is impossible to have a complete description of a complex environment with only a single scan. Then, the laser-scan data are merged (i.e., registered or aligned) together into a common coordinate system (Olsen et al. 2011). This is achieved by finding the geometric transformation which leads each laser-scan data to a reference one, so that the registration error at the overlapping regions is driven to a minimum (Makadia et al. 2006). Finally, the registered laser-scan data are integrated into a single coordinate system in which redundant information at the overlapping regions is merged. This is huge and also contains redundant parts like overlapping regions.

These data characteristics may affect that the final 3D object model can lack accuracy and details. Likewise, they pose challenges in determining the exact location of the pipelines (detection of 3D points corresponding to the pipelines) to enable the reconstruction of their geometry (Hammoudi et al. 2009). Therefore, 3D data processing for the identification of the pipelines and 3D pipeline model generation requires not only accurate algorithms, but also ones

that are both fast and robust (Gomez-Garcia-Bermejo et al. 2013).

3. Commercial Tools

Several commercially available software programs have been developed to automate the current manual process of 3D modeling:

The most laser scanning system providers (e.g., Leica Geosystems and Trimble) have developed software programs containing several functions that enable the pipe modeling from 3D point clouds. For example, the latest version of Leica Cyclone 8.1 by Leica Geosystems provides user interface (see Fig. 1) for pipe modeling with several functions such as automatic pipe finder, region growing from the selected 3D points for cylindrical objects, fitting cylinder, and creating models from the selected 3D point clouds. It contains various geometry types that can be created for the purposed of pipe modeling, for example, cylinder, elbow, reducing elvow, cone, torus, reducer (eccentric and concentric), and pipe tee.

Chunmei et al. (2009) and Qiusheng et al. (2010) used Cyclone (version was not specified) by Leica Geosystems to model the as-built pipelines from laser-scan data. In the study by Chunmei et al. (2009), they used noise removal function to eliminate some noise before pipe modeling. Then, users manually segmented each pipeline from the complicated pipe net and used 'fitting cylinder' function to model the each segmented pipeline consisting of straight and bend parts. In their study, they discussed that prior knowledge (design data) is required when some parts of the as-built pipelines are missing in the acquired 3D point clouds due to self-occlusion and occlusion by other objects. In the study by Qiusheng et al. (2010), users manually select 3D point clouds corresponding to the pipeline and used region growing function to find the boundary of the each selected pipeline. After the boundary of the each selected pipeline is found, users used 'fitting cylinder' function to model the pipeline.

The Trimble RealWorks provides the "EasyPipe" tool for pipe modeling by extracting 3D points for cylindrical objects and fitting cylinders to them. Then, elbows can be aligned and connected to the modeled pipes.

In addition to this, Leica Geosystems released several plug-in tools for pipe modeling from 3D point clouds, Leica CloudWorx AutoCAD Pro 5.0, Leica CloudWorx for Revit version 1.0.2, and Leica CloudWorx Microstation 4.0. By using these plug-in tools, it is now enable to import

and process the 3D point clouds inside the AutoCAD, Revit, and Microstation. Especially, they provide several functions for pipe modeling, such as 'pipe fit' to generate cylinders based on least-squares fitting from the selected 3D point clouds and 'connect pipe' to connect cylinders with elbows.
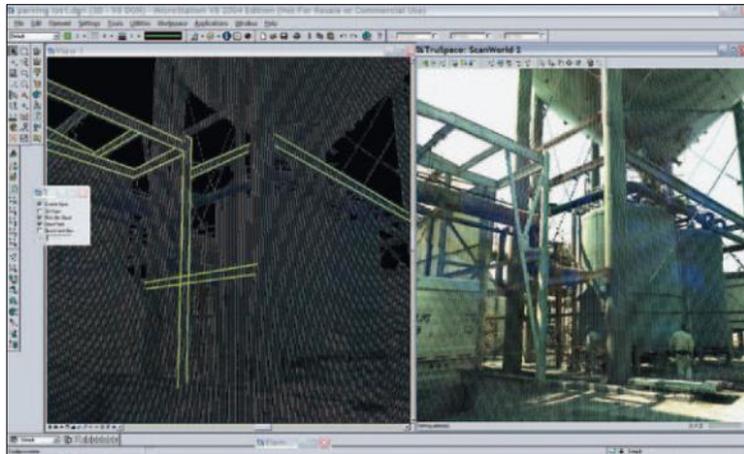

Fig. 1. Leica CloudWorx by Leica Geosystems

The leading 3D CAD venders (Autodesk, Benteley, Aveva, and Intergraph) have developed software programs containing several functions that enable the pipe modeling from 3D point clouds. For example, using AutoCAD Plant 3D together with Kubit's PointSense Plant add-in to AutoCAD enables the pipe modeling from 3D point clouds (see Fig. 2). PointSense Plant by Kubit provides several functions for pattern recognition that can identify pipelines from 3D point clouds. Then, users manually model the as-built pipelines by fitting CAD objects to the segmented 3D point clouds.
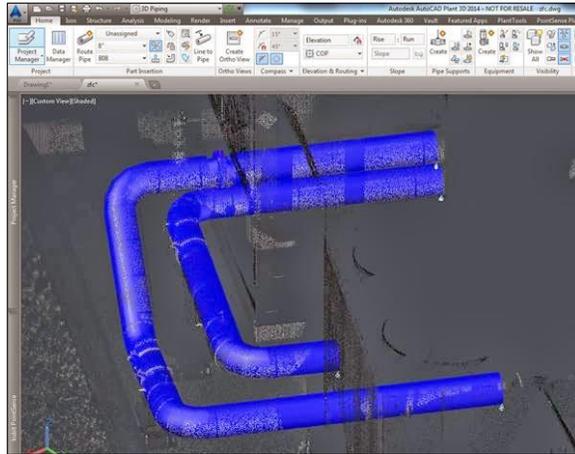
Fig. 2. AutoCAD Plant 3D by Autodesk

SmartPlant 3D by Intergraph has the similar functionality as AutoCAD Plant 3D together with Kubit's PointSense Plant add-in to AutoCAD (see Fig. 3). By using the fitting function, cylinders can be fitted automatically by manually selecting the 3D point clouds by calculating the best fit for the objects. In addition, the cylinders can be placed manually, and then the function decides the orientation and extent of the cylinders by evaluating the point cloud.
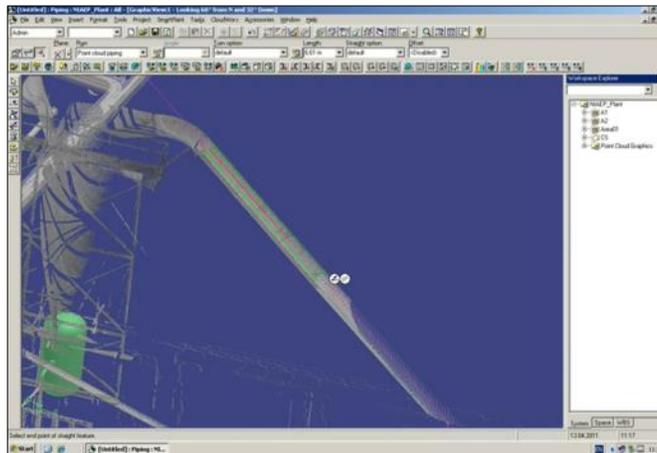

Fig. 3. SmartPlant 3D by Intergraph

These programs provide user-friendly environments for the 3D reconstruction of as-built pipelines as well as several functions to manipulate the 3D point clouds acquired by laser scanners, and create and modify the pipeline models (Chunmei et al. 2009). However, large 3D

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point clouds are not easily managed and processed due to their size of data they contain. In such environment, large 3D point clouds needs to be divided into several smaller parts in order to be manageable. Recently, Autodesk ReCap provides an efficient mechanism for managing such large 3D point clouds by managing them using different file formats (e.g., RCS and RCP).

The recent development of EdgeWise Plant™ 4.0 provides a function to automatically detect the straight portion of a pipeline and fit cylinders into it (see Fig. 4). It provides an powerful engine that can handle large 3D point clouds. However, these improvements have been limited to only the straight portion of the pipeline whereas the entire pipeline includes many forms of pipes. Hence, significant user intervention, which is undesirable, is still required to identify the different forms (other than straight) of the pipe as well as uncover any undetected straight pipes that need to be modeled.

Fig. 4. EdgeWise Plant^{TM} 4.0 by ClearEdge3D

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These reconstruction programs are in common use but are not fully automated, as they rely on substantial operator input/intervention to reconstruct an as-built 3D model (Tang et al. 2010). Although some programs provide semi-automated functions such as region growing, the user still has to mark certain portions of pipeline to indicate that they are to be modeled manually (Heinz et al. 2001; Rabbani 2006). To exploit potential advantages of an as-built 3D pipeline model, it is necessary to accurately measure the dimensions of installed pipelines and efficiently generate an as-built 3D pipeline model (Reisner-Kollmann et al. 2010). However, marking portions of individual pipelines by using an enormous and complicated set of laser-scan data is very time consuming and labor intensive. Furthermore, it is difficult to identify individual pipelines from laser-scan data, because pipelines of various radii, lengths, and orientations can be installed in complex configurations. According to a study conducted by Fumarola and Poelman (2011), it took 15 days to generate a 3D model for 2,602 objects (planes, cylinders) by a semi-automatic modeling process. In a study of modeling of the revamping of a Chevron installation, which was done using laser scanning, 40% of the total modeling cost was spent on data-processing labor (Sanders 2001).

4. Challenging Research Issues and State-of-the-Art

As a demand for digital reconstruction for large as-built 3D pipelines is increasing in the industry, several methods for reconstructing 3D pipelines have been proposed in last few decades. The previous research studies that have been done to reconstruct 3D pipelines range from semi-automated (Johnson et al. 1997; Veldhuis and Vosselman 1998; Navab and Appel 2006; Masuda and Tanaka 2010; Reisner-Kollmann et al. 2010) to fully-automated (Bosché 2003; Rabbani et al. 2006; Kawashima et al. 2012; Lee et al. 2013). They are based on more efficient survey methods, such as photogrammetry and laser scanning, than on traditional manual surveys.

In the semi-automated methods developed in the previous research studies (Johnson et al. 1997; Veldhuis and Vosselman 1998; Navab and Appel 2006; Masuda and Tanaka 2010; Reisner-Kollmann et al. 2010), 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 the pipelines, such as straight pipes, elbows, tees, etc. to be modeled. This process involves

manual selection of vertices, center lines, edges, or regions of the desired portions of the pipelines. Next, these manually selected vertices, center lines, edges, or regions are used as input for automatic estimation of the pose of the desired portions in 3D space and calculation of parameters, such as their radiuses and lengths, to reconstruct the desired portions by the computer.

Veldhuis and Vosselman (1998), Navab and Appel (2006), Reisner-Kollmann et al. (2010) proposed semi-automated methods based on photogrammetry, which enable 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. Veldhuis and Vosselman (1998) and Navab and Appel (2006) only focused on the reconstruction of straight pipe portions in the pipelines. Although Veldhuis and Vosselman (1998) proposed a method for reconstruction of elbows conceptually, they tested only the method involving the reconstruction for straight pipe portions. Reisner-Kollmann et al. (2010) proposed a method that allows for the reconstruction of entire pipelines, but in the form of tubes without boundaries between the different types of pipes, such as straight pipes, elbows, tees, etc.

The semi-automated methods based on photogrammetry require correspondences of vertices, center lines, edges, or regions across multiple images to reconstruct the desired portions in 3D. Therefore, the user should manually measure the edges of every straight pipe (Veldhuis and Vosselman 1998) or the centerlines of every pipeline (Reisner-Kollmann et al. 2010) to be reconstructed in a series of digital images. For example, in the computation for the reconstruction process proposed by Veldhuis and Vosselman (1998), every straight pipe needs to be measured manually in at least four images; two points on the edges of a straight pipe in two images are a minimum requirement to reconstruct the straight pipe. In the experiment by Veldhuis and Vosselman (1998), they used 8 images and manually measured 256 edges (16 edges for each pipe) for the reconstruction of 16 straight pipes. In their study, they recommended increasing the number of images and the number of measured edges of each straight pipe in order to improve the reconstruction quality.

In the semi-automated methods based on photogrammetry, there is a primary assumption that a series of digital images is already pre-calibrated, and the methods highly depend on pre-calibration. For this calibration, markers should be attached in advance to each of the desired

portions of the pipelines to be modeled (Navab and Appel 2006; Reisner-Kollmann et al. 2010) (see Fig. 5 and 6). In addition, both intrinsic and extrinsic parameters of the cameras also should be provided. These tasks, which include the identification of the correspondences of 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 tangled and enormous facilities that include a large number of pipelines.

| (a) | (b) |

Fig. 5. (a) An images of a part of an oil refinery. The occluding edges of nine straight pipelines are marked in the image. These edges are used to estimate the relative orientation of the image. (b) Cylinder reconstruction from three images (adapted from Navab and Appel 2006)

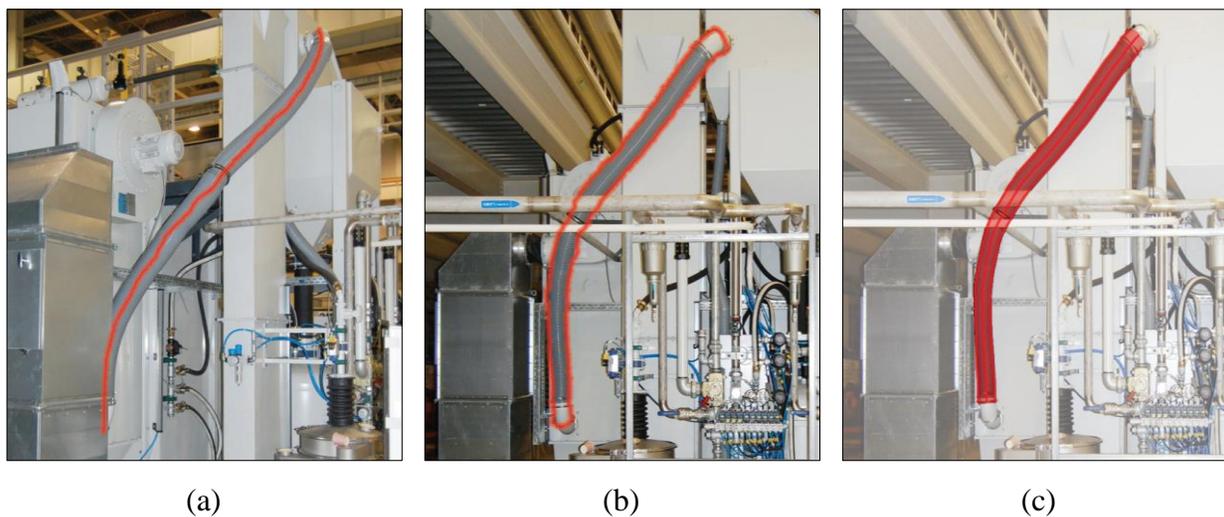
| (a) | (b) | (c) |

Fig. 6. (a)–(c) A tube with 30 control points is modeled by an edge (181 sample points) and a region (277 sample points) in two images (adapted from Reisner-Kollmann et al. 2010)

With the improvement of laser scanning, Johnson et al. (1997) and Masuda and Tanaka (2010) proposed semi-automated methods that allow for the reconstruction of as-built pipelines from laser-scan data acquired from industrial plants. Compared with photogrammetry, laser scanning provides explicit, dense 3D point cloud by directly and quickly measuring the 3D position and shape of as-built pipelines (Kawashima et al. 2012). Recent progress on laser scanning has made it possible to automatically capture large-scale 3D point cloud from a broad range of areas (Masuda and Tanaka 2010).

In the study by Johnson et al. (1997), the user manually selects and draw rectangular regions around the desired portions of the pipelines, such as straight pipes, elbows, tees, etc. to be modeled in a series of range images acquired from many different viewpoints. Next, smooth surface mesh models are generated for the drawn regions of interest, and they are registered into 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. Registered surface mesh models for the drawn regions of interest can be recognized once CAD drawings have been provided for each type of pipe, such as straight pipes, elbows, tees, etc. If the desired portions differ too much from the given CAD drawings, they cannot be recognized and modeled. Finally, after the drawn regions of interest are identified, each type of pipe is modeled by manually rotating and orientating it to locate the given CAD drawings in the actual position and with the proper orientation of the desired portion in 3D space (see Fig. 7).
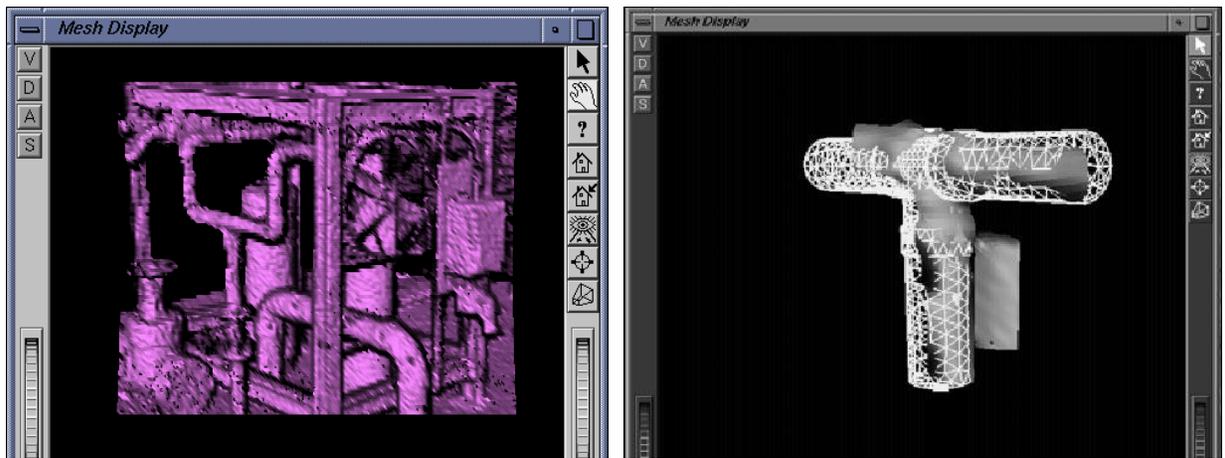
(a)   (b)

Fig. 7. (a) Shaded views of a scene surface mesh before processing; (b) Recognized objects
(wireframe) superimposed on scene data (shaded) for a model selected from the model library
(adapted from Johnson et al. 1997)

In the study by Masuda and Tanaka (2010), smooth mesh models are first generated from laser-scan data automatically. Then the missing portions in mesh models, which are due to the limited number of viewpoints or because of partial occlusion between a large number of objects, are manually compensated based on the reflected images. These reflected images have the form of unit spheres so that they can be converted to two types of images: a perspective image for users and a rectangular image by Mercator projection for computation. The user intuitively selects a seed region such as is included in desired portions on a perspective image; then the corresponding pixels on a rectangular image are detected automatically. At that point, the desired portions are modeled by fitting a surface to vertices in the selected seed region and searching the adjacent vertices that lie on the surface through the region-growing method when the user specifies the desired portions' locations and sizes according to industrial standards (see Fig. 8).
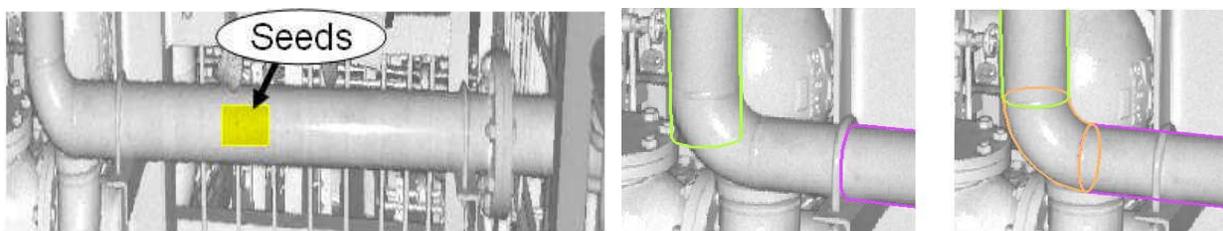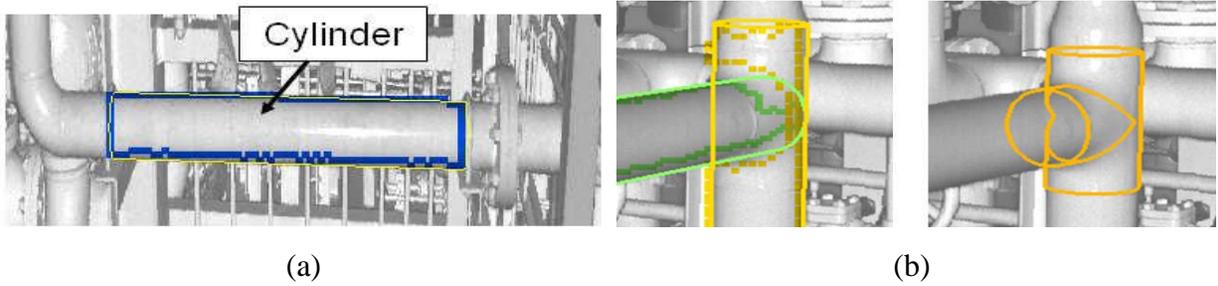
Fig. 8. (a) Region growing on a perspective image, (b) Generating cylindrical features (adapted from Masuda and Tanaka 2010)

- Semi-automated methods/ Laser scanning (challenges and limitations)

Although a lot of user input is involved in the semi-automated modeling process, of course, this is possible only if all of the straight pipes or pipelines are visible without the portions partially occluded by other objects that are prevalent, in most of methods based on either photogrammetry or laser scanning. In addition, an inherent drawback of these studies is that the reconstruction is error-prone if the user makes a mistake or the user input is not accurate enough (Reisner-Kollmann et al. 2010). Even the previous studies based on photogrammetry have fundamental limitations: their use is limited to straight pipe portions or entire pipelines as tubes without boundaries between the different types of pipes; therefore, it is difficult to use them for reconstruction of the entire 3D pipeline, which is divided into a series of straight pipes connected with elbows, tees, or etc. Although both of the research studies based on laser scanning take a major step forward in reference to reconstructing the entire 3D pipeline, they still require 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 when it is done in a semi-automated way with manual intervention.

To this end, several research studies (e.g., Bosché [2003]; Rabbani et al. [2006]; Kawashima et al. [2012]; and Lee et al. [2013]) have been initiated to automate the generation of a 3D as-built pipeline model. These studies have yielded similar advancements in terms of automatic performance.

Bosché (2003) proposed an automated method that enables reconstruction of as-built straight and curved pipes from laser-scan data acquired from the surrounding pipe-spools of buildings (see Fig. 9). Bosché's method iteratively fits and matches all cylindrical pipes by adopting the

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method proposed by Kwon (2002). 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.

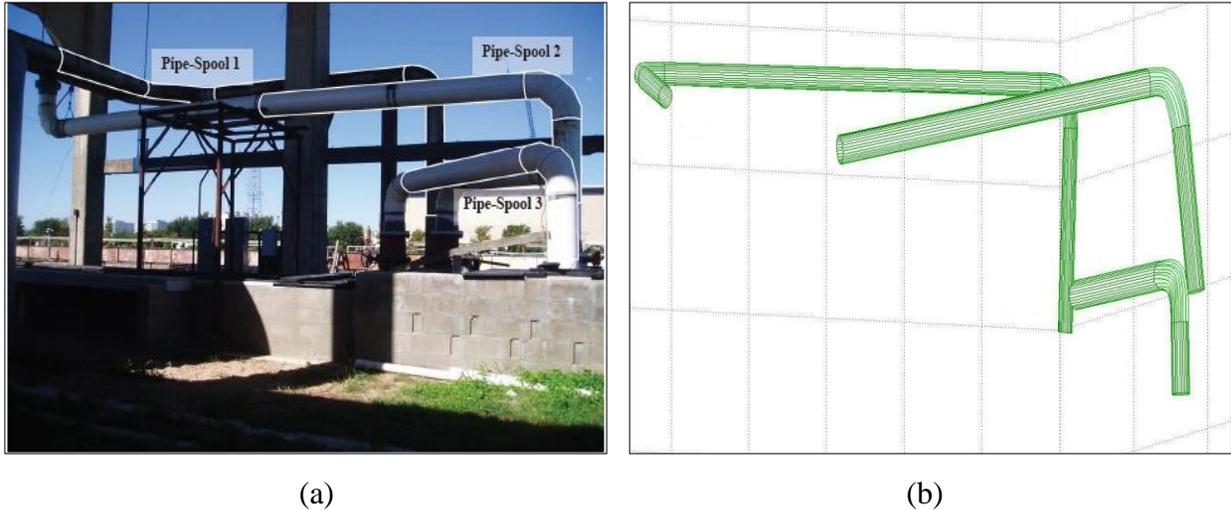(a)   (b)

Fig. 9. (a) Picture of the scene with scanned highlighted pipe-spools; (b) Hypothetical result, with elbows, of the modeling spell checker on the pipe-spool 1 (adapted from Bosché 2003)

Rabbani et al. (2006) proposed an automated method that enables reconstruction of as-built cylindrical pipes from laser-scan data acquired from industrial plants (see Fig. 10). In their study, segmentation of the point clouds 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.
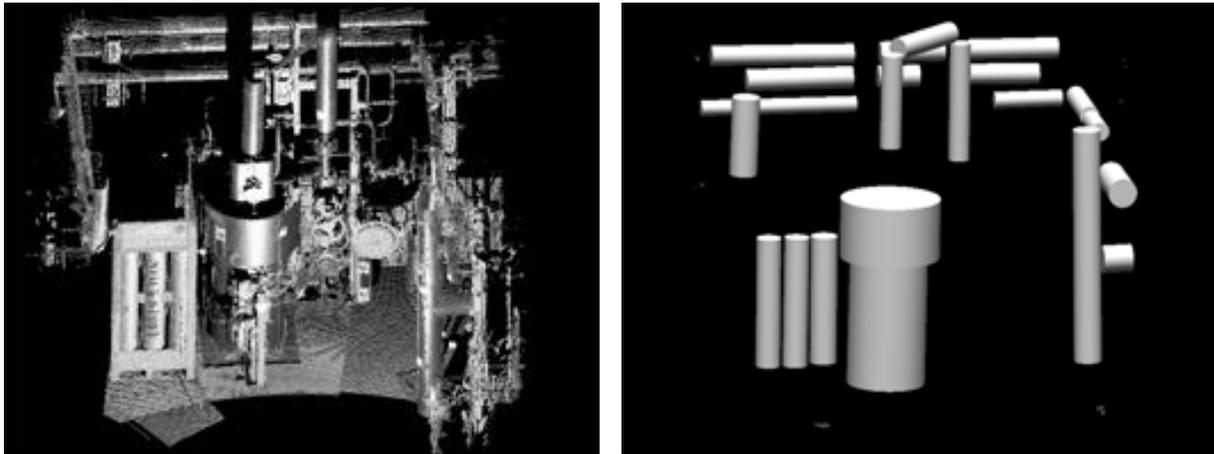
(a)   (b)

Fig. 10. Results of the Hough transform for cylinder detection (a) Input point cloud; (b) Results
of cylinder detection (adapted from Rabbani et al. 2006)

Kawashima et al. (2012) also proposed an automated method that enables reconstruction of
as-built pipelines from laser-scan data acquired from industrial plants. In their study, 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 (see Fig. 11). 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 the axes of the straight pipes. Based on these connection
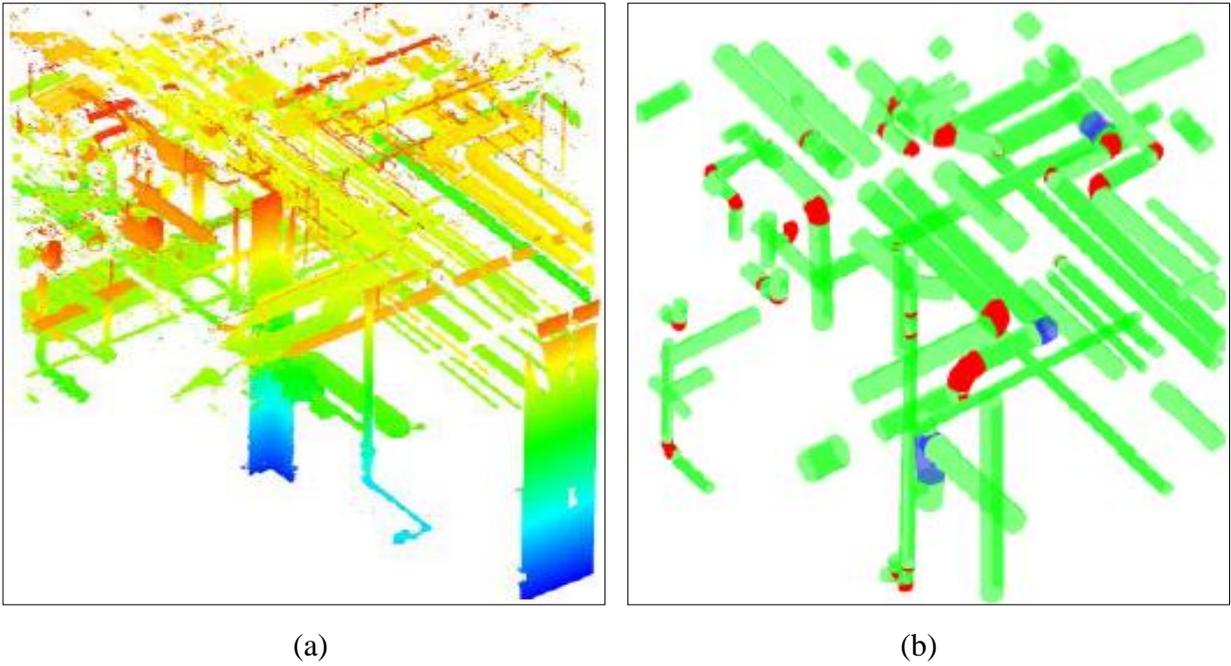relationships, other types of pipes, such as elbows and tees, are modeled.

| (a) | (b) |

Fig. 11. (a) Scanned point cloud; (b) Recognition result of piping system (adapted from Kawashima et al. 2012)

Lee et al. (2013) proposed an automated method that enables reconstruction of as-built pipelines composed of straight pipes, elbows, and tee pipes from laser-scan data. In their study, in order to extract accurate skeletons of individual pipelines from laser-scan data, estimation of the skeleton candidates using a Voronoi diagram is proposed. Then, extraction of skeletons from the skeleton candidates is performed using a topological thinning. The extracted skeletons are segmented into their individual components, and a set of parameters for the individual components are calculated.

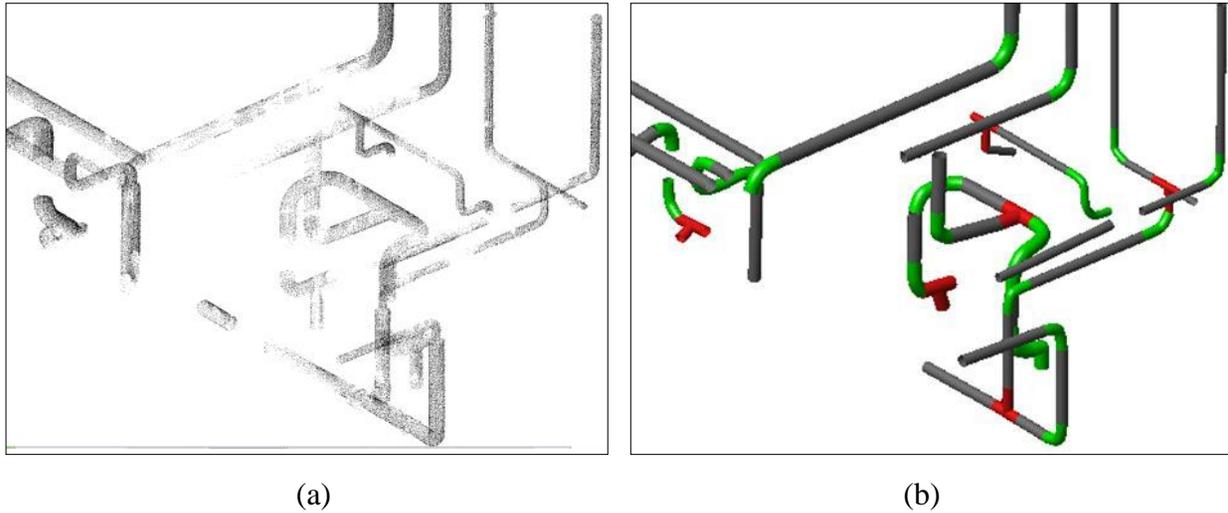<div align="center">(a)   (b)</div>

Fig. 12. (a) Scanned point cloud; (b) Modeling results (adapted from Lee et al. 2013)

- Automated methods/ Laser scanning (challenges and limitations)

The previous methods are limited to only parts of an entire 3D pipeline, for example, straight pipes, elbows, and tees in the most recent study by Lee et al. (2013). Although the study by Kawashima et al. (2012) attempted to achieve an improvement in terms of the completeness of the generated models of the entire 3D pipelines, 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. (2012) and Lee et al. (2013), the detection of the as-built pipelines from laser-scan data 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 repetitive, tedious, and even trivial tasks typically performed in the manual 3D reconstruction of as-built pipelines can be eliminated using automated approaches. However, there is still a need for an effective, fully automated 3D reconstruction method that can model the entire pipeline, irrespective of the types of its constituent parts.

5. Future Research Opportunities

6. Concluding Remarks

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