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Automatic segmentation and 3D modeling of pipelines into constituent parts from laser-scan data of the built environment

Hyojoo Son, Changwan Kim *

Department of Architectural Engineering, Chung-Ang University, Seoul 156-756, Republic of Korea

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ABSTRACT

The demand for three-dimensional (3D) modeling of as-built or as-is pipelines that occupy large areas in operating plants has been growing in recent times. In practice, although measurements can be efficiently performed by the use of laser-scanning technology, generating a pipeline model from laser-scan data remains challenging, possibly due to the data characteristics. This paper proposes a method for generating 3D models of entire pipelines, including straight pipes, elbows, reducers, and tee pipes, from laser-scan data. The proposed method comprises three main tasks: (1) identifying the existence and location of entire pipelines from laser-scan data, (2) segmenting each pipeline surface into its constituent forms (straight pipe, elbow, reducer, and tee), and (3) reconstructing the geometry of the individual pipelines and generating a 3D model of it. Field experiments were performed at two different operating industrial plants to validate the method. Evaluation of the quantitative results reveals that the proposed method can indeed be used for the automation of 3D modeling of the pipelines in industrial plants—and to be capable of producing such models with high accuracy.

1. Introduction

To be of significant utility in the operation, maintenance, and retrofitting of a plant facility, a three-dimensional (3D) model of an as-built or as-is (hereafter referred to as "as-is") pipeline at an existing plant should provide detailed information on each of its distinct components – straight pipes, elbows, reducers, and tees – including their diameters, lengths, orientations, and locations [1–3]. In some cases, piping components are periodically replaced in the course of preventive maintenance. In others, unplanned, emergency repairs or replacements may be required after accidents or failures. When a single pipeline among a network of pipelines requires maintenance, repairs, and/or replacements, the 3D as-is model allows the facility manager to easily locate the pipeline and ensure that it is correctly repaired and maintained [4,5]. Moreover, older pipes within an existing plant facility may need to be retrofitted – or new ones may need to be added – in order to increase production that stems from capacity expansion and/or process integration [6], 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-is environment [7]. Additionally, the locations of the pieces of the equipment and the surrounding environment should be considered. In this process, an accurate 3D model is useful for discerning the as-is condition of the pipelines and for planning modifications before a costly modification of existing facilities is undertaken [8].

Measurements can now be efficiently performed using a laser-scanning technology [9,5,10–12]; however, it is still challenging to model the pipelines from laser-scan data in practice. The current methodology is labor intensive and subject to certain limitations in the recording of the as-is condition of the pipelines [13]. Even the manual modeling process becomes tedious when a large number of pipelines are involved, especially those that are constituents of complicated pipeline networks. In addition, such a laborious process poses challenges in updating the model to reflect changes in the as-is condition, potentially leading to a discrepancy between the created models and the as-is condition.

Several commercially available software programs have been developed to assist the current manual process of 3D modeling (e.g., Leica CloudWorx by Leica Geosystems, AutoCAD Plant 3D by Autodesk, and EdgeWise Plant by ClearEdge3D, all of which were introduced in 2014). These programs are user-friendly tools for the 3D modeling of the pipelines, provide several features for manipulation of laser-scan data in the form of 3D point clouds acquired from the built environment, and have the capability to create and modify pipeline models to help and guide users in what would otherwise be a repetitive, tedious, and time-consuming modeling process [14]. For example, a recent version (i.e., 4.0) of the EdgeWise Plant software includes a variety of features for executing detection of the straight portion of a pipeline and for fitting cylindrical shapes to it. Although these developments have shown that the entire modeling process can be speeded up and can be efficiently performed by automating part of the modeling process, these features are applicable to only the straight portion of a pipeline, whereas an actual pipeline can include different forms of pipes. Hence, significant user intervention is still required, both to identify pipes

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* Corresponding author. Tel.: +82 2 820 5726; fax: +82 2 812 4150.
E-mail address: changwan@cau.ac.kr (C. Kim).

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that are not straight and to uncover any undetected straight pipes that need to be modeled.

Several research studies (e.g., Bosché [15]; Rabbani et al. [16]; Lee et al. [17]; Kawashima et al. [3]; Ahmed et al. [18]) to address automation of the generation of a 3D as-is pipeline model have been undertaken. Previous attempts to address this problem have advanced the state of the art in terms of both the level of automation (from semi-automated methods to fully automated methods) and the degree of completeness of the model (by including additional forms of pipe). The results of these efforts have shown that certain repetitive, tedious, and time-consuming tasks that were traditionally performed by manual 3D modeling of the pipelines can now be eliminated by use of automation. However, the development of an effective and fully automated 3D modeling method that has the capability to model an entire pipeline irrespective of the types of its constituent parts has been lacking.

In this paper, a fully automated method for the generation of 3D models of entire pipelines comprising straight pipes, elbows, reducers, and tee pipes is proposed and validated. The key concept behind this method is the use of information about the local curvature of the surface of a pipeline. The modeling process consists of identification of pipelines from complicated laser-scan data, segmentation of each pipeline into its constituent pipe forms, modeling of the geometry of the individual pipelines, and generation of a 3D model of the entire pipeline network. The rest of the paper provides an overview of the proposed method for the 3D modeling of the pipelines and a detailed description thereof, presents the experimental results, outlines the conclusions of the study, and points to directions for future research.

2. Related work

Several existing research studies (e.g., Bosché [15]; Rabbani et al. [16]; Lee et al. [17]; Kawashima et al. [3]; Ahmed et al. [18]) address automation of the generation of a 3D as-is pipeline model.

Bosché [15] proposed an automated method that models some parts of the pipelines from laser-scan data. The targeted components are straight pipes and elbows. The modeling process proposed by Bosché consists of three steps. First, the positions and orientations of straight pipes are found, by iterative fitting and matching procedures. For this purpose, the fitting and matching methods proposed by Kwon [19] were adopted. In this first step, the radii of these straight pipes are also estimated. Then the positions of other straight pipes or elbows that are connected to the straight pipes are inferred, by analyzing their positions and orientations relative to the adjacent straight pipes. Finally, the positions of the components found with this approach are corrected by considering the connectivity among these other connected straight pipes or elbows. Boschè tested their method in an experiment on pipe-spools that surround buildings.

Rabbani et al. [16] also proposed an automated method that models some parts of the pipelines from laser-scan data. The targeted components are straight pipes only. In their proposed modeling method, a 3D point cloud is first segmented on the basis of a smoothness constraint which considers spatial connectivity and similarity of surface normals. Then the positions and orientations of the straight pipes are found, and their radii are estimated as well, by using the 3D Hough transform proposed by Rabbani et al. Finally, a 3D CAD model of a cylindrical shape is fitted to each of the straight pipes found. Rabbani et al. tested their method in experiments on pipelines in industrial plants.

Lee et al. [17] proposed another automated method that models some parts of the pipelines from a 3D point cloud for the pipelines only. The targeted components are straight pipes, elbows, and/or tees. In their modeling method, Lee et al. first estimate candidates for the skeletons of individual pipelines by using Voronoi diagrams. From the estimated candidates, the skeletons of individual pipelines are calculated by using a topological thinning algorithm. Then segmentation of the calculated skeletons is done, in order to recognize different forms of pipe (i.e., straight pipes, elbows, and/or tees). Finally, 3D models for the straight pipes, elbows, and/or tees are generated by estimating a set of parameters for each of the components. Lee et al. tested their method in experiments on pipelines in industrial plants.

Kawashima et al. [3] proposed an automated method that models some parts of the pipelines from laser-scan data. The targeted components are straight pipes, elbows, and/or tees. The modeling process they proposed consists of three steps. First, 3D points corresponding to the pipelines are detected from laser-scan data using normal-based region growing. Then the positions and orientations of straight pipes are found by analyzing eigenvalues and the surface-normal vectors of a 3D point cloud. In this step, the radii and positions of these straight pipes are also estimated. Finally, the positions and orientations of elbows and/or tees connected to the straight pipes are found, on the basis of the spatial connectivities between them, and 3D models for those elbows and/or tees are generated. Kawashima et al. tested their method in experiments on pipelines in industrial plants.

Ahmed et al. [18] proposed an automated method that models some parts of the pipelines from laser-scan data. The targeted components are straight pipes only. In their modeling method, a 3D point cloud is sliced at regular intervals, and the sliced portions are projected in a direction orthogonal to a main axis of the building to which the pipes are connected. Then the positions of straight pipes are found, and their radii are estimated, by using a Hough transform. In this process, Ahmed et al. considered that most straight pipes are built in directions orthogonal to the main axes of a building facility. In this way, searching for circles in planes perpendicular to these axes for the purpose of detecting pipes with standard reference diameters reduces the problem to two dimensions. Ahmed et al. tested their method in an experiment on pipelines in building facilities.

The aforementioned studies have yielded similar advancements in terms of automatic performance that eliminates at least some user involvement, but the methods proposed in those studies are limited to only certain parts of a pipeline. Ahmed et al. [18] modeled straight pipes that are either perpendicular or parallel to the ground. Only straight pipes (but no others) were modeled in the study by Rabbani et al. [16], and straight pipes and elbows (but not reducers and tees) were modeled in the study by Bosché [15]. To date, the method proposed by Lee et al. [17], has been shown to be an improvement over the studies by other researchers in terms of the completeness of the generated pipeline models (i.e., straight pipes, elbows, and tees), but it did not include reducers. In the study by Kawashima et al. [3], the targeted components were also limited to straight pipes, elbows, and tees (i.e., they did not include reducers). Also, the modeling results are largely depends on the parameters used in the modeling process. Depending the parameters, recall ranged from 60% to 92% in their experiments. Therefore, the development of an effective and fully automated 3D modeling method that can model an entire pipeline, irrespective of the types of its constituent parts (straight pipes, elbows, reducers, and tees) was not achieved in any of these studies.

3. Segmentation and 3d modeling of pipelines

The laser-scan data acquired being acquired from a plant facility could be incomplete, owing either to complex occlusion [20,16,6,3], or to the presence of noise because of the reflections from shiny surfaces of pipes and other industrial parts. In addition, some applications provide only a single scan of an object, so that only a fraction (at most half) of the pipeline's surface is scanned. These disadvantages pose challenges in determining the exact locations of pipelines—an important step in the modeling of their geometry. This paper proposes and validates an automated method for the generation of a 3D model of an entire pipeline that comprises a series of straight pipes connected by any/all of the following types of pipe: elbows ($\pi/4$ rad, $\pi/2$ rad, and $3\pi/4$ rad), reducers (concentric and eccentric), and tees (straight, Y, cross, equal, and reducing). The method proposed in this study is an extension of our previous study [21], which enabled modeling of only straight pipes, $\pi/2$ rad elbows,

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