Automation in Construction 35 (2013) 199–207

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Skeleton-based 3D reconstruction of as-built pipelines from laser-scan data

Joohyuk Lee, Hyojoo Son, Changmin Kim, Changwan Kim *

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

ARTICLE INFO

Article history:
Accepted 16 May 2013
Available online 16 June 2013

Keywords:
3D reconstruction
As-built modeling
As-built pipeline
Laser scanner
Skeleton-based modeling

ABSTRACT

There has been a growing demand for an as-built 3D pipeline model. Although several studies on automation of the process of reconstruction of as-built 3D pipelines have been carried out, previous approaches have been limited to the generation of only a portion of an entire 3D pipeline. The aim of this study was to propose an automated approach to the generation of as-built 3D pipeline models of entire pipelines composed of straight pipes, elbows, and tee pipes from laser-scan data. First, the skeletons of individual pipelines are extracted. Then the extracted skeletons are segmented into their individual components, and a set of parameters for them are calculated. The experimental results show that the proposed approach is robust to incompleteness of the laser-scan data, as well as to noise and to density variations in the data. As a result, the proposed method enables the generation of reliable as-built 3D pipeline models.

1. Introduction

There has been a growing demand for an as-built 3D model for pipelines. Not only do pipelines typically comprise a large portion of the facility at which they are located, but the pipeline system plays an important role in the facility's operations [1–3]. As-built 3D pipeline models could be used for many applications, including inspection and revamping of an existing facility, as well as in creation/updating of as-built documentation for a new structure. In each case, accurate information on the dimensions and other properties of the as-built pipeline are essential for revamping of the existing facility [4]. By using a precise as-built 3D pipeline model, proper planning can be made for modifications, thereby preventing unwanted collisions between new pipelines and those that are currently installed. In addition, up-to-date models are needed for inspection of an installed pipeline [5], so that deviations in its location or dimensions from those in an as-built pipeline model can readily be detected. Also, accurate as-built documentation can be created by reflecting deviations from an as-planned pipeline design that do not conform to dimensional tolerances or that otherwise reflect construction-phase design changes in the as-built 3D pipeline model [6]. An as-built 3D pipeline model that reflects such deviations from the as-planned pipeline design can then be used as accurate as-built documentation for purposes of rebuilding, facility upgrading, or generation of information updates [7].

The traditional method for generating an as-built 3D pipeline model involves the use of theodolites to measure the dimensions of the installed pipelines [1]. 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 [8]. 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 [1]. As a result, the traditional method of measuring pipelines has been restricted to localized use [8].

With recent developments in laser-scanning technology, problems with measuring the dimensions of pipelines have been rectified. Various commercially available software programs for providing an as-built pipeline reconstruction from laser-scan data have been developed, including Laser Modeller [9], CADWorx [10], and Cyclone [11]. 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 [12]. 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 [13,14]. 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 [15]. 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

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

0926-5805/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.autcon.2013.05.009

[16], it took 15 days to generate a 3D model for 2602 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 [17].

Clearly, a method for automatically generating an as-built 3D pipeline model from laser-scan data needs to be developed [18] — one in which the entire process is automated (without operator intervention) and that can be put into practice effectively and seamlessly. A great deal of research efforts on automatic generation of 3D pipeline models has recently been conducted (see, for example, Bosché [19], Rabbani et al. [20], Kawashima et al. [18], ClearEdge 3D [21]). These research studies have yielded advancements over previous methods in terms of automation. However, these improvements have been limited to the generation of only a portion of an entire 3D pipeline (which can include many forms of pipe). Thus, generation of a fully automated 3D pipeline model from laser-scan data has continued to be a challenging and laborious problem.

The aim of this study was to propose a fully automated approach for the generation of as-built 3D pipeline models of entire pipelines composed of straight pipes, elbows, and tee pipes from laser-scan data. The rest of the paper is organized as follows: Related work that has been conducted on generation of 3D pipeline models from laser-scan data is briefly discussed in Section 2. In Section 3, an overview and details of the proposed method for generating 3D pipeline models are provided. In Section 4, experimental field results obtained by use of the proposed 3D pipeline modeling method are presented. Finally, conclusions and recommendations for future research are given in Section 5.

2. Related work

Several research studies have been done on automation of the entire process of reconstruction of as-built 3D pipelines (see, for example, Bosché [19], Rabbani et al. [20], Kawashima et al. [18]). The fully automated methods proposed in these studies retain the advantages of using efficient survey methods based on laser scanning, and they aim to eliminate any user intervention.

Bosché [19] 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. Bosché's method iteratively fits and matches all cylindrical pipes by adopting the method proposed by Kwon [22]. 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.

Rabbani et al. [20] proposed an automated method that enables reconstruction of as-built cylindrical pipes from laser-scan data acquired from industrial plants. 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.

Kawashima et al. [18] 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. 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.

The feature that these research studies have in common is that the methods they have proposed are major improvements over previous methods in terms of automation performance. However, the methods proposed by Bosché [19] and Rabbani et al. [20] are limited to only part of an entire 3D pipeline: straight pipes and elbows (but not tees) in the study by Bosché [19], and just straight pipes in the study by Rabbani et al. [20]. Although the method proposed by Kawashima et al. [18] is an improvement over the other two studies in terms of the completeness of the generated model of the entire 3D pipeline, only 55% of the individual pipes contained in the 3D pipeline in their experiment (other than the straight pipes) were correctly modeled as their actual types of pipe. Kawashima et al. [18] concluded that their proposed method was less robust to partial occlusion, since the occluded portions were treated as separate objects in their experiment. In addition, their method can be much more dependent on the density of the 3D point cloud than is the case with other methods, since the starting point of the reconstruction of an entire 3D pipeline in the method proposed by Kawashima et al. [18] is the extraction of points on straight pipes, which is based on estimation of surface-normal vectors.

The attempts made thus far to address the problem of the reconstruction of 3D as-built pipelines 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, time-consuming, and even trivial tasks typically performed in the manual reconstruction of 3D as-built pipelines can be eliminated in favor of automated approaches. However, there is still a need for an effective, fully automated method of reconstruction of an entire 3D pipeline which is composed of a series of straight pipes connected to one another by elbows and/or tees.

3. Methodology

The purpose of this research was to propose and develop an automated approach that uses laser-scan data to model an entire 3D as-built pipeline comprised of a series of straight pipes connected by elbows or tees. Our proposed method is an improvement over approaches that were limited to modeling of only part of a complete 3D pipeline, in that it is capable of modeling an entire 3D pipeline and employs the concept of the skeleton as an important descriptor of the geometrical and topological properties of a pipeline. In addition, the entire process of modeling a 3D pipeline is accomplished automatically, with no manual intervention.

The basic principle behind the proposed approach is that each type of pipe form, such as a straight pipe, an elbow, or a tee, is defined by its skeleton. The skeleton of a 3D object is an abstract representation of the geometrical and topological properties of its 3D shape [23]. In the case of a pipe, the skeleton consists of its so-called central axis, which defines its position and orientation, and a set of pertinent parameters [24,25]. For example, a cylindrical straight pipe is defined by the central axis of the cylinder plus its radius and length. A curved tube (elbow) is defined by the symmetry of the central axis plus an angle and its radius. A tee is formed by connecting a cylindrical branch pipe to a cylindrical main pipe at the point of intersection. Therefore, a tee pipe is defined by the central axes of the main and branch pipes plus their radii and lengths.

Based on these concepts, laser-scan data can be used to generate the skeleton of an entire 3D pipeline model from the skeletons of the straight pipes, elbows, and tee pipes of which the pipeline is comprised. This approach involves two processes: extraction of the skeletons and calculation of the set of parameters for each pipeline. Fig. 1 illustrates the proposed approach for the entire 3D pipeline modeling process.