Advanced Engineering Informatics 37 (2018) 163–174

Contents lists available at ScienceDirect

Advanced Engineering Informatics

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

Review article

A review of 3D reconstruction techniques in civil engineering and their applications

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ARTICLE INFO

Keywords:
3D reconstruction techniques
Civil engineering
Point clouds
Achievements
Challenges

ABSTRACT

Three-dimensional (3D) reconstruction techniques have been used to obtain the 3D representations of objects in civil engineering in the form of point cloud models, mesh models and geometric models more often than ever, among which, point cloud models are the basis. In order to clarify the status quo of the research and application of the techniques in civil engineering, literature retrieval is implemented by using major literature databases in the world and the result is summarized by analyzing the abstracts or the full papers when required. First, the research methodology is introduced, and the framework of 3D reconstruction techniques is established. Second, 3D reconstruction techniques for generating point clouds and processing point clouds along with the corresponding algorithms and methods are reviewed respectively. Third, their applications in reconstructing and managing construction sites and reconstructing pipelines of Mechanical, Electrical and Plumbing (MEP) systems, are presented as typical examples, and the achievements are highlighted. Finally, the challenges are discussed and the key research directions to be addressed in the future are proposed. This paper contributes to the knowledge body of 3D reconstruction in two aspects, i.e. summarizing systematically the up-to-date achievements and challenges for the applications of 3D reconstruction techniques in civil engineering, and proposing key future research directions to be addressed in the field.

1. Introduction

Three-dimensional (3D) reconstruction is the process of generating 3D representations of the 3D appearance of objects from the outputs of data collection equipment [1,2]. Generally, the 3D representations are in the form of point cloud models, mesh models and geometric models, among which, point cloud models are the basis. Because the techniques are both efficient and cost-effective [3] for obtaining 3D representations of objects, they have been applied in many fields, such as surveying engineering [4], medical engineering [5]. In recent years, they have been applied in civil engineering as well. For example, the 3D models generated from applying the techniques have been used for the preservation of historical buildings [6–8], for analyzing the energy efficiency of buildings [9], and for acquiring the surface texture of pavements [10]. However, such applications are still in the early stage and it is anticipated that their potential is large. To enhance such applications, it is essential to clarify the status quo of the research and application of the techniques through literature review.

3D reconstruction techniques in civil engineering and their applications have been summarized in a number of review papers. Tang et al. [11] summarized the 3D reconstruction techniques for creating as-built building information models (BIM) through the point clouds from laser scanners. Lu and Lee [3] reviewed the image-based techniques for constructing as-is BIM for existing buildings. But in the two reviews, they did not go to the detailed process of some steps, such as point cloud preprocessing and mesh reconstruction. In addition, they confined their target objects to only buildings. Parn and Edwards [12] reviewed the principles, cost, specifications and applications of laser scanning, i.e. progress tracking, quality assessment, structural health monitoring and creating as-built BIM. Son et al. [13] reviewed the applications of the 3D reconstruction techniques based on photos, videos and laser scanning, i.e. dimensional quality control, progress tracking and reconstruction of Mechanical, Electrical and Plumbing (MEP) systems.

The other techniques that are relevant to 3D reconstruction techniques in civil engineering and their applications, have also been summarized in some publications. Teizer [14] summarized the computer vision based personnel tracking, equipment tracking and detection on construction sites. Koch et al. [15] reviewed the computer vision based defect detection and condition assessment of civil infrastructure, including reinforced concrete bridges, precast concrete tunnels, underground concrete pipes and asphalt pavements. Koch et al.

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https://doi.org/10.1016/j.aei.2018.05.005
Received 30 September 2017; Received in revised form 4 March 2018; Accepted 17 May 2018

[16] presented current achievements and open challenges in the machine vision-based inspection of large concrete structures. In all these three reviews, 3D reconstruction techniques were involved as one of the methods. Mathavan et al. [17] reviewed the 3D imaging-based technologies for pavement distress detection and measurements, where 3D reconstruction-related techniques including stereo imaging, laser scanning and structured light systems are involved.

In the above-mentioned review papers, two important aspects about 3D reconstruction techniques are missing: (1) some important steps for 3D reconstruction techniques, including feature matching, camera motion estimation and absolute scale recovery; (2) the key research directions of the techniques and their applications in the future. Among them, the steps in the former aspect have been regarded to be indispensable in a specific research [18], while the latter aspect is obviously important to the civil engineering community. Taking into account of such limitations, this paper systematically summarizes 3D reconstruction techniques and the up-to-date achievements and challenges for the applications of the techniques in civil engineering and proposes key future research directions in the field.

The remainder of this paper focuses on the process, algorithms and methods of 3D reconstruction techniques, and their achievements and challenges in civil engineering. In Section 2, the methods used for literature retrieval and for determining the research scope are introduced, and the framework of the techniques in civil engineering is illustrated. Sections 3 and 4 present the techniques for 3D reconstruction, including the techniques for generating point clouds and that for processing point clouds respectively, particularly the corresponding algorithms and methods. Section 5 presents the applications of the techniques in reconstructing and managing construction sites and reconstructing pipelines of MEP systems as typical examples, and highlights the achievements. Section 6 discusses the challenges of applying the techniques in civil engineering and proposes the key research directions to be addressed in the future. Section 7 concludes the paper.

2. Methodology

2.1. Literature retrieval conditions

The major databases in the world, including Web of Science, Engineering Village and China Knowledge Resource Integrated Database, are retrieved by using keywords including '3D reconstruction', 'three-dimensional reconstruction', 'three dimensional reconstruction' and '3-D reconstruction' to obtain a list of publications dating from 2000 to the present. Since the keywords do not confine the target objects of the research and application of 3D reconstruction techniques in civil engineering, these publications are then filtered through reading the abstracts to exclude those that are not related to the areas of civil engineering.

2.2. Research scope

By analyzing the publications obtained from Section 2.1, 95 publications in total, the frequency of publications in terms of data collection equipment types is shown in Table 1.

It deserves to explain that laser scanners are also known as Light Detection And Ranging (LiDAR) [18,19]. Because the phrase 'laser scanners' is more frequently used than the word 'LiDAR' in the reviewed publications, 'laser scanners' is chosen to be used from here on in this paper.

According to the table, monocular cameras, binocular cameras, video cameras and laser scanners have been used with high frequency for 3D reconstruction techniques in civil engineering, while CT, ultrasonic tomography, Kinect and total stations have been rarely used. In order to focus on the major 3D reconstruction techniques, only the techniques that are applied in civil engineering and based on the following data collection equipment, i.e. monocular cameras, binocular cameras, video cameras and laser scanners, are reviewed in this paper.

Table 1
The frequency of publications in terms of data collection equipment types per five years since 2000.

Data collection equipment types	2000–2004	2005–2009	2010–2014	2015-prseent	Total
Monocular cameras	–	4	22	15	41
Binocular cameras	–	3	3	3	9
Video cameras	–	2	7	1	10
Laser scanners	–	3	15	9	27
Computerized Tomography (CT)	–	1	1	2	4
Ultrasonic tomography	1	–	–	1	2
Kinect (based on structured light)	–	–	–	1	1
Total stations	–	–	1	–	1
Total	1	13	49	32	95

The 3D reconstruction techniques based on monocular cameras, binocular cameras and video cameras can be classified into two categories according to their principles, i.e. point-based ones and line-based ones. In the former, the feature points in the outputs of monocular cameras, binocular cameras and video cameras are extracted and processed in subsequent steps [19–21], while in the latter, the feature lines in the outputs of monocular cameras, binocular cameras and video cameras are extracted and processed in subsequent steps [22–27]. Because the latter category of 3D reconstruction techniques has very few applications up to now, this category is not reviewed in this paper.

In case some algorithms and methods need to be quoted, other publications except the 95 publications have also been cited in this paper, for example, the publication on Scale Invariant Feature Transform (SIFT) algorithm.

2.3. Framework of 3D reconstruction techniques in civil engineering

Through reviewing the selected publications, the framework of 3D reconstruction techniques in civil engineering is established as shown in Fig. 1.

In the framework, the 3D reconstruction techniques are divided into two big steps, i.e. generating point clouds and processing point clouds, and each big step can be further divided into several steps. In the former big step, the outputs of monocular cameras, binocular cameras and video cameras are processed to generate the point clouds corresponding to a certain scene. In the latter big step, point clouds obtained from the previous big step or that from laser scanners are processed to generate the outputs of 3D reconstruction techniques for the objects of interest in the scene. In order to make it easy to read, the 3D reconstruction techniques will be reviewed in this big step-and-step framework, with Sections 3 and 4 dedicated to the two big steps, respectively.

3. Techniques for generating point clouds

In general, the inputs of 3D reconstruction techniques are the outputs of data collection equipment. The inputs of the techniques with high frequency in civil engineering are monocular images, stereo images, video frames and point clouds, corresponding to monocular cameras, binocular cameras, video cameras and laser scanners, respectively. It deserves to explain, although monocular images, stereo images and video frames are all digital images, they have different characteristics. Indeed, stereo images contain monocular images in pair, while video images contain a series of monocular images, or a series of stereo images. In this section, the processes of generating point clouds from monocular images, stereo images and video frames and algorithms and methods used in these processes are presented. Since the