



Polygonization of point clouds of repetitive components in civil infrastructure based on geometric similarities[☆]

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1. Introduction

Planning and execution of maintenance activities are important for prolonging the service life of civil infrastructures. Many civil infrastructures are approaching their end of service lifetimes and efficient methods for their maintenance are required. Traditional maintenance approaches primarily use 2D drawings and paper-based inventories, which entail several problems. For example, 2D drawings are difficult for inexperienced operators to be visually perceived. In addition, paper-based inventories are less reliable, and it is difficult to search for specific data in paper-based inventories. In order to maintain a large portfolio of old civil infrastructures, easy and efficient methods of maintenance are required.

Recently, 3D models and digital records have been used for maintenance activities [1,2,3]. The use of digital models enables civil infrastructure to be represented in 3D, and by using digital data, various simulations can be executed for tasks such as safety evaluation. Building Information Modeling (BIM) is an emerging lifecycle information management method that is contributing to the efficient maintenance of buildings [4]. Construction Information Modeling

(CIM) [5], which is similar to BIM, consolidates all lifecycle information of civil infrastructures into 3D digital models. These product models are represented primarily by Industry Foundation Classes (IFC) [4]. The IFC is a data format that can be used by various software applications in the architecture, engineering, and construction (AEC) industries, and various product models have been proposed based on IFC for structures such as bridges [6] and harbors [7]. The CIM framework can be used for the efficient maintenance of existing civil infrastructures. However, as-built 3D models are required for CIM, and models of many existing civil infrastructures are not readily available. For such civil infrastructures, even if 2D drawings exist, translating these drawings into 3D models is difficult. Moreover, the models may not reflect the as-is layout of the civil infrastructure due to modifications that have been made over time. Therefore, methods to efficiently create as-is 3D models of existing civil infrastructures are needed.

The use of laser scanning technology is one possible solution for obtaining 3D data of existing civil infrastructures. Laser scanners can acquire surface information of objects as a set of points with attributes (e.g., the color and reflectance intensity of the laser). These point clouds, which provide as-is geometric information of the scanning

[☆] This paper introduces a novel technique for the polygonization of point cloud data of civil infrastructure based on geometric similarity between components. The resulting polygon model can be used for Building Information Modeling (BIM)/Construction Information Modeling (CIM) and contributes to the efficient and easy management of many existing civil infrastructures. The proposed method finds regions of the point cloud that match the input query template polygons in order to identify similar components of the infrastructure and then segments the identified regions and replaces them with template polygons. The query polygons are either found within the input point cloud or created by tools, such as photogrammetry or CAD. The proposed method is designed and tuned for civil infrastructures that have multiple repeated similar components and stand vertically on the ground. In the present study, the proposed method is applied to two real-world case studies of a monorail and a harbor structure, and the results obtained using three types of query polygon are compared.

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targets, should be converted to polygon models for CIM applications. A Mobile Mapping System (MMS) is often used for scanning urban environment, and it is used for scanning elongated structures such as roads, tunnels and monorails. The number of points of these structures is usually large, and the point clouds often involve defects caused by occlusions. In this paper, creating polygon data from the MMS point data of large and with repetitive components is focused.

Creating polygons from a point cloud is referred to as surface reconstruction and is one of the emerging topics in geometric modeling (see a survey by [8]). For that, signed scalar fields from the points are usually defined and zero-level set of the scalar fields are found. However, these methods usually create a single polygon from an input point cloud. Generally, product models consist of several parts and additional post-processing activity, such as segmentation, is required. Moreover, point clouds of the target civil infrastructures acquired by MMS are usually large and difficult to polygonize all at once. Memory overflow may also prevent direct polygonization of large structures with sufficient accuracy. Although this problem can be resolved by grid clustering, all decomposed clusters should eventually be reassembled, and unexpected artifacts may appear on the boundary of the clusters. Another approach to reduce memory-related problems is to decompose the point cloud by fitting primitive surfaces (e.g., plane and cylinder) by methods such as RANSAC [9]. However, types of supported surfaces are limited.

An alternative approach is to decompose a point cloud into meaningful regions prior to polygonization. For example, Matsuoka and Masuda [10] proposed a method by which to identify road points in the point cloud of a city based on the height of the points. Xiong et al. [11] proposed a method for classifying point clouds of an indoor environment into walls, floors, ceilings, or clutter based on machine learning. The primary advantage of such methods is the decomposition of point clouds into segments containing a smaller number of points, which enables easier polygonization. However, machine learning usually requires extensive training data.

The primary objective of the present research is to automatically create a polygonal model from point cloud data of large and elongated civil infrastructures acquired by MMS for the use in CIM applications. In the present paper, a new method to create polygonal models based on geometric similarity is proposed. On the assumption that civil infrastructures have multiple similar parts, such as bridge piers and concrete ribs, the proposed method uses a shape matching technique (e.g., [12]) for decomposing point cloud data into similar segments and replacing these segments with template polygons to create a model. The proposed framework consists of four main steps. After pre-processing of an input point cloud, shape matching is used to find regions in the input point cloud that are similar to template polygons of the components of the structure. Next, the point cloud is segmented into identified regions that contain the point clouds of the components. Finally, each region is replaced by its corresponding template polygon. Using the proposed method, there are three approaches to create template polygons: (1) the *photogrammetry-based* approach uses input 3D template models created by photogrammetry methods (e.g., Structure from Motion (SfM)), (2) the *CAD-based* approach uses input 3D template models created by modeling applications, and (3) the *self-matching* approach creates representative polygonal models of components only from the input point cloud data. These approaches are partly based on our previous work (i.e., [13,14]). In addition to these, in the present paper, various new techniques to improve the accuracy and efficiently of each of these approaches are proposed. For example, with respect to the CAD-based approach, a novel fitting operation to adjust the shape of template models to the point cloud is investigated.

The novel main contribution of this paper is to propose a novel modeling framework that uses the shape matching. The point cloud data of civil infrastructures are large and often include noises. These points prevent direct polygonization by state-of-the-art methods of surface reconstructions. Whereas the proposed method places of

template polygons of the components, and the polygonization is only applied per template. This enhances the polygonization of huge point clouds. In addition, the placement of templates has the potential to fill in missing sections of scanned data, which enables the creation of product models from incomplete scanning data. The proposed framework is flexible in accepting multiple input templates. Furthermore, the new geometric fitting technique is capable of adjusting roughly designed templates to the point cloud.

In the present paper, real-world case studies, including a harbor breakwater and a monorail facility, are used to validate the proposed method.

2. Literature review

2.1. Generation of 3D point clouds

BIM/CIM models are used for efficient construction management. For existing infrastructures, as-built models created from scanned point cloud data are commonly used. There exist several challenges for creating as-built BIM/CIM models. One of the main challenges is the data collection of target infrastructures. Stationary laser scanners and MMS are common devices for this purpose. Since these devices are expensive for average construction companies, photogrammetry-based point acquisition is also being used. Dai et al. [15] reported comparison of photogrammetry-based methods and time-of-flight-based laser scanner, and concluded the former methods are cost-effective and have enough accuracy for limited applications. Following this, Koch et al. [16] summarized the current achievements and challenges of vision-based inspection systems including data collection, recognition and detection of degradations. According to their research paper, photo collection in outdoor environment achieves reasonable accuracy, although environmental factor (e.g., lighting, illuminations and viewport distance) affects its performance. Briliakis et al. developed a progressive scanning system using videogrammetry [17]. The proposed compact system uses two laptop-equipped cameras for stereo-based 3D reconstruction and inter-frame correspondence construction. Since the user can easily carry their system, the occlusion problem is not a major challenge.

2.2. Point cloud data processing

The first step to convert point cloud data to 3D model objects is to create surface models in the form of polygons. The conversion of point cloud data to polygons is known as *surface reconstruction* problem (see a survey of [8]). Major approaches find isosurfaces of implicit functions computed from point cloud data with normal vectors. There exist various definitions of implicit functions, for example, the signed distance function [18], the radial basis function [19,20,21], and the Poisson equation [22,23]. These methods usually create a single surface from the input point cloud data. If the data of an assembled polygon with separate parts are required, surface reconstruction is applied to already decomposed regions, or surface segmentation is applied to the created polygon model.

Segmentation is a problem of decomposing input data into meaningful parts, and is a well-studied topic for input data such as images [24,25], meshes [26], and points [27]. A basic segmentation strategy is to find discontinuities (e.g., in the intensity, curvature, and other attributes) in the input data as the boundary of the region. For instance, region growing [28] and watershed [29] algorithms can be used to expand a region from a seed point based on user-defined criteria (e.g., normal difference or pixel values as depth). If the boundary of a region is unclear, energy-minimization optimization functions can be used. For example, active contour models [30] and the level set method [31] compute the boundary by minimizing energy functions. Graph-cut [32] defines the neighbor relationship as a graph structure with cost, and computes segmentation by minimum-cut of the graph.

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