ISPRS Journal of Photogrammetry and Remote Sensing xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Automatic 3D reconstruction of electrical substation scene from LiDAR point cloud

Qiaoyun Wu[a], Hongbin Yang[a], Mingqiang Wei[a], Oussama Remil[a,c], Bo Wang[d], Jun Wang[a,b,*]

[a] Nanjing University of Aeronautics and Astronautics, China
[b] Huaiyin Institute of Technology, China
[c] Ecole Militaire Polytechnique, Algeria
[d] Chuzhou University, China

ARTICLE INFO

Keywords:
LiDAR point cloud
Electrical substation scene
Automatic 3D reconstruction
Pattern detection
Shape retrieval

ABSTRACT

3D reconstruction of a large-scale electrical substation scene (ESS) is fundamental to navigation, information inquiry, and supervisory control of 3D scenes. However, automatic reconstruction of ESS from a raw LiDAR point cloud is challenging due to its incompleteness, noise and anisotropy in density. We propose an automatic and efficient approach to reconstruct ESSs, by mapping raw LiDAR data to our well-established electrical device database (EDD). We derive a flexible and hierarchical representation of the ESS automatically by exploring the internal topology of the corresponding LiDAR data, followed by extracting various devices from the ESS. For each device, a quality mesh model is retrieved in the EDD, based on the proposed object descriptor that can balance descriptiveness, robustness and efficiency. With the high-level representation of the ESS, we map all retrieved models into raw data to achieve a high-fidelity scene reconstruction. Extensive experiments on large and complex ESSs modeling demonstrate the efficiency and accuracy of the proposed method.

1. Introduction

The proliferation of the light detection and ranging (LiDAR) technique facilitates the reconstruction of large-scale outdoor scenes. A variety of applications benefit from this advanced technique, such as robotic navigation, regular monitoring, inspection planning, data management, and renovation planning.

Traditional modeling methods enforcing on the LiDAR point cloud require complicated interactions, e.g., manual labeling and the creation of surfaces and their connections. Therefore, they are time-consuming. While recent automatic methods (Golovinskiy et al., 2010; Ruwen et al., 2010; Nan et al., 2010; Livny et al., 2010; Shao et al., 2012; Pang et al., 2015) have yielded promising results, the reconstructed geometry of input scenes has not yet reached the level of quality required for use in fully-automated content creation. To be slightly more challenging, in this paper we struggle for the automatic 3D reconstruction of an electrical substation scene (ESS) from raw LiDAR data with defects of typical clutter, missing parts and noise.

In contrast to urban scenes which are relatively piecewise flat and indoor scenes containing a limited number of categories, ESS as a kind of industrial scene, is more complicated in its 3D structures and categories. Existing modeling methods (Nan et al., 2012; Kim et al., 2012; Wang et al., 2016) cause troubles in industrial scenes. There are several reasons for this issue – some of which are fundamental problems – in object recognition, as would be required for correct modeling, based purely on existing object representation that designed for simple structures, of which the descriptiveness decreases with the increasing categories of industrial devices.

In this paper, we present a simple, yet effective approach to reconstruct a large-scale ESS. We can discover recurring patterns in LiDAR data and exploit them to speed up the large-scale ESS reconstruction, since ESS is invariably characterized by high repeatability of alignments (Arastounia and Lichti, 2015). Our algorithm proceeds with two phases. First, in the hierarchical pattern detection phase, we start by detecting and removing the ground plane and the transmission power lines. After that, all disjoint electrical devices can be obtained based on spatial clustering. With these clusters, we design a hierarchical subgraph matching scheme to reliably detect repetitive patterns in the scene. All repetitive objects are detected and a virtual representation of the scene is simultaneously generated. Second, in the shape retrieval phase, to tackle the challenge of reconstructing high-quality geometry, we focus on leveraging strong shape priors in the form of a large electrical device database (EDD) containing a variety of clean, hand-modeled 3D shape data. Objects are modeled through recognition, with

* Corresponding author at: Nanjing University of Aeronautics and Astronautics, China.
E-mail address: davis.wjun@gmail.com (J. Wang).

https://doi.org/10.1016/j.isprsjprs.2018.04.024
Received 1 October 2017; Received in revised form 3 April 2018; Accepted 28 April 2018

Please cite this article as: Wu, Q., ISPRS Journal of Photogrammetry and Remote Sensing (2018), https://doi.org/10.1016/j.isprsjprs.2018.04.024

a 3D object recognition process that matches clusters of 3D points to objects stored in the database. In the recognition stage, a new global 3D shape descriptor is designed, which provides an appropriate trade-off between descriptiveness and efficiency, and supports accurate 3D object retrieval. With all retrieved models and the hierarchical representation of the scene, a complete and detailed reconstruction can be achieved. A range of challenging real-world scenes have been tested to demonstrate the effectiveness of our method.

Our main contributions are as follows:

- We propose an EDD-assisted framework for fast and automatic modeling of large-scale electrical substation scenes from raw LiDAR data.
- We present a hierarchical pattern recognition algorithm to reliably detect the reoccurring devices in EESs, which significantly reduces computation time.
- We design a novel object descriptor supporting accurate 3D object recognition, even for a scan with quintessential density anisotropy, noise and occlusions.

1.1. Related works

Extensive studies relevant to 3D modeling focus on primitive geometry (Triebel et al., 2005; Osswald et al., 2011), street structures (Golovinskiy et al., 2010; Alexander Patterson et al., 2008) and indoor objects (Nan et al., 2012; Ruhnke et al., 2010). However, relatively fewer take on industrial part detection (Pang and Neumann, 2013, 2015), where objects are often more complex with a wide variety of shapes and structures. Here, we review previous works that are most closely related to ours, in particular those on the use of repetition detection and shape retrieval techniques for large-scale scene reconstruction.

Scene reconstruction. In recent years, automatic modeling of large-scale scenes has captured growing attention and resulted in many applications in various fields. The interactive SmartBoxes tool proposed in (Nan et al., 2010) utilizes the regularity of facades to quickly assemble detailed 3D primitives through a discrete optimization balancing between data fitting and structural regularity terms. However, this work is limited by the variety of architectural models. Nan et al. (2012) presented an algorithm for recognition and reconstruction of scanned 3D indoor scenes. Their work first searches and classifies the scene by iteratively accumulating patches that form regions with high classification likelihood, followed by deforming templates to fit to the classified point cloud and select the best matching template. The feature designed for classifying provides good separability and discernibility characteristics with regards to daily objects in indoor scenes, for industrial devices, which is less descriptive. Kim et al. (2012) took advantage of object repeatability to reconstruct indoor scenes approximately by modeling indoor objects with simple primitives (e.g., planes, boxes, cylinders). Gonzalez-Aguilera et al. (2012) employed photogrammetric techniques and a terrestrial laser scanning system to model power equipment in electrical substations. Nevertheless, the generation of a neat CAD model is not automatic, since the coverage provided by a single image is limited. Shao et al. (2014) abstracted indoor environments as collections of cuboids and hallucinated geometry in the occluded regions by globally analyzing the physical stability of the resultant arrangements of the cuboids. While results are impressive, the generated scene geometry is not sufficient for high-quality shape retrieval, due to the primitive type limitation. Furthermore, their algorithm could fail when a large imbalance among object densities occurs, which is common for industrial objects with tall heights. Pang et al. (2015) presented a method for the automatic modeling and recognition of a 3D industrial site point cloud. Their work divides the modeling into three independent processes: pipe modeling, plane classification, and object recognition, which supports the multi-mode display. The modeling results are promising. However, the efficiency is adverse, due to the exhaustive 3D scanning-window search for each object in the scene. In contrast, we focus on the electrical substation scene reconstruction by first exploring the regularities of input scenes, and then exploiting them to speed up the reconstruction.

Repetition detection. Regularity exploration in 3D scenes has recently gained extensive attention. Quite a few techniques have been specifically developed for discovering regularity from images (Müller et al., 2007; Cai and Baciu, 2013), 3D geometry (Pauly et al., 2008; Triebel et al., 2010) and indoor/outdoor scenes (Berner et al., 2008; Kerber et al., 2013). Müller et al. (2007) presented an image-based procedural modeling method for urban facades which extracts the high-level facade structure in a image by detecting repetitions. Cai and Baciu (2013) proposed a translation symmetry detection method for images, based on the analysis of invariant repetitive patterns, which demonstrates fabulous detection performance in highly curved or distorted symmetry structures. Pauly et al. (2008) presented an approach to detect repetitive structures in 3D geometry. By designing an optimization algorithm for detection, their work is proven to be robust to outliers, missing data and substantial clutters. Their simultaneous registration guarantees a high degree of accuracy of the extracted transformations which, on the other hand, results in an expensive computational burden. Triebel et al. (2010) proposed an unsupervised technique to segment and discover objects of multiple occurrences, where an object is defined as a constellation of object parts. Schindler et al. (2008) exploited the fundamental properties of repeating patterns throughout all stages of their algorithm – detection, matching, and pose recovery – to overcome the problems normally associated with highly repetitive environments. Kerber et al. (2013) presented a method for detecting partial symmetries in large scenes. The key idea is to design the feature descriptors for each sample point and then to perform clustering based on the similarity of descriptors, such that the method is able to locate all symmetry points. A recent work (Wang et al., 2016) formulates the repetition detection as an energy optimization function, balancing geometric errors, regularity and complexity of facade structures simultaneously. The detected regularities and geometric constraints of facade structures can significantly facilitate the whole framework. However, the work is based on the observation that the repetitions are arranged in grid, which is exceedingly common for urban facade scenes. Our repetition detection technique is inspired by the pioneering work of Berner et al. (2008), which applies graph-based matching techniques to detect symmetries in geometric objects. They combined the novel randomized graph matching algorithm with a general feature detection technique and achieved the reliable symmetry detection. However, in a noisy and incomplete scene, when they decided to take an edge, they used a transformation matrix to copy a small piece of geometry to the target edge. Only if ICP converges there, is the edge taken. This process inevitably increases the computation cost. Electrical substations as a kind of representative industrial infrastructure, demonstrate significant regularity in the layouts of electrical devices. For raw substation scenes, which are complicated due to the obstruction of a large number of transmission lines among objective repetitions, Pauly et al. (2008) and Wang et al. (2016) can both produce excellent detection results but with the efficiency defect. On the other hand, these raw scenes can be clear and elegant after the removal of the ground plane and the additional transmission power lines, which is accessible, since the stereoscopic effects are more distinct than urban facades. Therefore, we first focus on removing all irrelevant objects from the raw scene and then construct an improved graph with each node representing an individual electrical device. With the graph, we explore all frequent patterns, which is called graph-based pattern recognition in our method. In each pattern, subgraphs are structurally isomorphic and thus once one subgraph is recovered, the rest can also be reconstructed.

Object descriptor. Object recognition in 3D scenes has been studied extensively for many years. Various methods tackle the 3D object recognition problem, among which some utilize machine learning techniques (Kim et al., 2012; Su et al., 2015; Li et al., 2016; Nan et al.,