ISPRS Journal of Photogrammetry and Remote Sensing 134 (2017) 15–29

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Pairwise registration of TLS point clouds using covariance descriptors and a non-cooperative game

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ARTICLE INFO

Article history:
Received 31 March 2017
Received in revised form 2 October 2017
Accepted 2 October 2017

Keywords:
Terrestrial laser scanning (TLS)
Registration
Covariance matrix descriptor
3D representation
Game theory

ABSTRACT

It is challenging to automatically register TLS point clouds with noise, outliers and varying overlap. In this paper, we propose a new method for pairwise registration of TLS point clouds. We first generate covariance matrix descriptors with an adaptive neighborhood size from point clouds to find candidate correspondences, we then construct a non-cooperative game to isolate mutual compatible correspondences, which are considered as true positives. The method was tested on three models acquired by two different TLS systems. Experimental results demonstrate that our proposed adaptive covariance (ACOV) descriptor is invariant to rigid transformation and robust to noise and varying resolutions. The average registration errors achieved on three models are 0.46 cm, 0.32 cm and 1.73 cm, respectively. The computational times cost on these models are about 288 s, 184 s and 903 s, respectively. Besides, our registration framework using ACOV descriptors and a game theoretic method is superior to the state-of-the-art methods in terms of both registration error and computational time. The experiment on a large outdoor scene further demonstrates the feasibility and effectiveness of our proposed pairwise registration framework.

1. Introduction

Terrestrial laser scanning (TLS) systems have been commonly used in many applications such as heritage preserving, 3D modeling, and manufacturing because a TLS system can rapidly acquire dense and accurate 3D point clouds with geometry, color and intensity information from surfaces. As a preprocessing step for many TLS point cloud related applications, registration aims to transform multiple scans in arbitrary initial positions and orientations into a common coordinate system to align their overlapping regions. Point cloud registration is indispensable for completing interest objects or scenes. This paper develops a method for automated pairwise registration of TLS point clouds.

Registration of TLS point clouds is a challenging task. First, the arbitrariness in initial positions of scans can affect the performance of point cloud registration methods and has to be considered in the operation. Second, the TLS data pose four major challenges as follows (Tam et al., 2013; Theiler et al., 2015; Yang et al., 2015): (1) **Data size**: A TLS system can rapidly acquire a large volume of point clouds (e.g., up to 300,000 pts/s). That means it needs to efficiently deal with a large amount of data. (2) **Noise and outliers**: Noise is presented as a form of random fluctuation of data or unwanted points close to a surface, and outliers are considered as those points far from the surface. Both noise and outliers are common and unavoidable. (3) **Uneven density**: Uneven distribution of point density is caused by the mechanism of the TLS system. That is, the closer the target is to the TLS system, the denser the acquired points are, and vice versa. (4) **Limited overlap**: Limited overlap is caused by different views in each scan. In particular, considering the efficiency of data acquisition, the number of scans is expected to be as low as possible, leading to insufficient common points between successive scans. All of these challenges can seriously affect the robustness of point cloud registration methods. Other problems may arise due to pattern repetitions in a scene or symmetries of a surface, which are inevitable and should be considered when designing a point cloud registration method.

In this paper, we propose a new pairwise registration method for TLS point clouds. Our method consists of two main stages: adaptive covariance (ACOV) descriptor generation and non-cooperative game construction. In the first stage, the method first

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https://doi.org/10.1016/j.isprsjprs.2017.10.001
0924-2716/

introduces the features to be fused in a covariance matrix and the keypoint extraction method based on covariance descriptors. Then, we propose a new ACOV feature descriptor. Finally, we introduce the distance metric and matching strategy used to find candidate correspondences between two point clouds. The second stage contains three steps: (1) the concept of game theory used for matching; (2) a non-cooperative matching game; and (3) an optimal solution for the matching game based on replicator dynamics. We tested our proposed method on three models and a large outdoor scene acquired by two different static TLS systems. Experimental results have demonstrated the effectiveness of our pairwise point cloud registration method. The contributions of this paper are as follows: (1) We propose a covariance-based descriptor to fuse various information (e.g., geometry, color, and intensity) acquired by a TLS system; (2) We generate covariance descriptors over adaptive neighborhood sizes, which are robust to noise, outliers, rigid transformations, and uneven density; and (3) We develop a game-theoretic matching method for pairwise registration of TLS point clouds. The remainder of the paper is organized as follows. Section 2 briefly reviews and discusses the representative works for pairwise point cloud registration. Section 3 introduces the pipeline of our registration method, including adaptive covariance (ACOV) descriptor generation and non-cooperative matching game construction. Section 4 presents the experimental results. Section 5 presents a detailed discussion of the derived results. Section 6 concludes the paper.

2. Related work on pairwise registration

Pairwise point cloud registration problem can be solved using a rigid transformation with six degrees of freedom by finding a set of correspondences (at least three) between two point clouds. A point cloud registration method usually composes of two steps: coarse registration and fine registration. Over the past decades, a number of pairwise point cloud registration methods have been proposed in different fields, such as computer vision, photogrammetry, and robotics. We will only review and discuss some representative works in this section. For a more complete overview, please refer to the evaluation papers (Salvi et al., 2007; Tam et al., 2013; Pomerleau et al., 2015; Weinmann, 2016).

The most commonly used fine registration methods include the Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992; Chen and Medioni, 1992) and its variants (Bae and Lichti, 2008; Gressin et al., 2013; Yang et al., 2013). Bae and Lichti (2008) proposed a Geometric Primitive ICP with Random sample consensus (GPICPR). It uses the normal vector and geometric curvature of a local surface for matching and neighborhood search. The GPICPR algorithm provides an acceptable efficiency and accuracy in finding correspondences for registration. Gressin et al. (2013) demonstrated how the standard ICP algorithm can be improved by geometric features. It is noticed that these ICP methods are able to achieve registration results with high accuracy and efficiency, but they still require a coarse alignment to avoid a local minimum. Therefore, Yang et al. (2013) proposed a global optimal solution for ICP-type registration (Go-ICP) without a coarse alignment by integrating the ICP algorithm with a branch-and-bound (BnB) scheme. The Go-ICP algorithm works well on small-scale point clouds, but it still faces challenges on large-scale point clouds acquired by a TLS system.

Aiger et al. (2008) proposed a method named 4-Points Congruent Sets (4PCS) for coarse registration. This method extracts coplanar 4-points sets which are congruent as primitives. The 4PCS algorithm is demonstrated to be robust to varying degrees of noise, outliers, and overlaps, but it has a quadratic time complexity. Mellado et al. (2014) proposed the SUPER-4PCS algorithm with linear time complexity using a smart indexing for data organization. Theiler et al. (2014) used keypoints (DoG and Harris detectors) to down-sample the original point clouds and then adapted the 4PCS algorithm for registration. Their experiments demonstrated that K-4PCS obtained a sufficiently high registration accuracy for the subsequent ICP refinement with a linear time complexity. In addition, these feature descriptors evaluated (Guo et al., 2014) are commonly used as matching primitives to find correspondences between two point clouds in RANSAC-based methods. Barnea and Filin (2008) exploited features which are invariant to 3D rigid-body transformation as primitives. Rusu et al. (2009) proposed a Sample Consensus based method for initial alignment (SAC-IA) using a local feature called Fast Point Feature Histograms (FPFH) as primitives. Weinmann et al. (2011) proposed an efficient perspective-n-point (EPnP) algorithm by extracting characteristic 2D points based on SIFT features. Yang and Zang (2014) extracted crest lines as matching primitives and then proposed a deformation energy model to find correspondences, they obtained fine registration results with good accuracy in their experiments. Kelbe et al. (2016) generated feature descriptors and tested the RMSE of a blind view-invariant marker-free registration method for TLS data in forest environments. Yang et al. (2016) proposed a registration method based on semantic feature points extracted from large-scale urban scenes.

Albarelli et al. (2009) proposed a game-theoretic perspective for the matching problem. The matching problem was formulated as a non-cooperative game where the potential correspondences are analogous to strategies, while payoffs represent the degree of compatibility between any two correspondences. Further, Albarelli et al. (2010, 2015) cast the selection of correspondences between two point clouds in a game-theoretic framework and obtained a fine registration in a single step. Cirujeda et al. (2015) proposed a covariance descriptor to fuse color and shape information within several neighborhood radii, called multi-scale covariance (MCOV) descriptor. The MCOV descriptor was then combined with a game theoretic framework to find correspondences under global geometric constraints. These game-theoretic methods can obtain a fine registration between small-scale point clouds in a linear time without any initial alignment. However, they cannot handle large-scale TLS point clouds.

Compared to (Cirujeda et al., 2015), this paper proposes a new feature descriptor called ACOV to fuse various information (e.g., geometry, color, and intensity) over an adaptive neighborhood size and develops an improved game-theoretic matching method by adding a Laplacian term for pairwise registration of TLS point clouds.

3. The proposed registration method

This section introduces a new registration framework for TLS point clouds, which consists of two stages: adaptive covariance (ACOV) descriptor generation and non-cooperative game construction.

3.1. Covariance matrix descriptor

The proposed method is expected to fully use the information (e.g., geometry, color, and intensity) of data acquired by a TLS system, by means of the statistical concept of covariance matrix. The covariance matrix is generalized to multiple dimensions to combine a set of random variables and to describe statistically how these variables change in relation to each other. From the descriptor perspective, random variables combined in a covariance matrix must correspond to a set of features computed at a given point. In this section, the extracted features and the covariance matrix (which works as a descriptor) will be introduced firstly. Then,