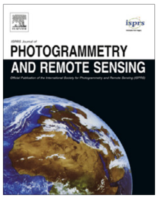
ISPRS Journal of Photogrammetry and Remote Sensing 95 (2014) 109–121

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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



Automated registration of dense terrestrial laser-scanning point clouds using curves

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ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form 23 March 2014
Accepted 23 May 2014

Keywords:
Shape similarity
Curve matching
Point cloud registration
Deformation energy model
Terrestrial laser scanning
Feature extraction

ABSTRACT

This paper proposes an automatic method for registering terrestrial laser scans in terms of robustness and accuracy. The proposed method uses spatial curves as matching primitives to overcome the limitations of registration methods based on points, lines, or patches as primitives. These methods often have difficulty finding correspondences between the scanned point clouds of freeform surfaces (e.g., statues, cultural heritage). The proposed method first clusters visually prominent points selected according to their associated geometric curvatures to extract crest lines which describe the shape characteristics of point clouds. Second, a deformation energy model is proposed to measure the shape similarity of these crest lines to select the correct matching-curve pairs. Based on these pairs, good initial orientation parameters can be obtained, resulting in fine registration. Experiments were undertaken to evaluate the robustness and accuracy of the proposed method, demonstrating a reliable and stable solution for accurately registering complex scenes without good initial alignment.

1. Introduction and literature review

Terrestrial laser scanners (TLS) are widely used in a variety of applications such as civil engineering, heritage documentation, transportation engineering, and landslide monitoring because they can capture dense radiometric and geometric data rapidly from a local scene. Nevertheless, multiple scans are necessary to obtain full coverage of a scene (e.g., a complex object) because of the scanner's limited field of view. Hence, registration between different scans must be performed to achieve a uniform coordinate reference frame, which is a precondition for scene reconstruction, segmentation, and classification.

Extensive studies have been carried out on registering scans from different locations (e.g., Chui and Rangarajan, 2000; Bae and Lichti, 2004; Dold, 2005; Gressin et al., 2013). Published registration methods can be classified into three categories: artificial marker-based methods, auxiliary data-based methods, and 3D radiometric point-based methods. Artificial marker-based methods are generally labor-intensive and time-consuming because the precise positions of the artificial markers must be manually measured as tie points for registration between different scans. Auxiliary data-based methods usually incorporate texture from imagery or depth imagery and point clouds for registration (e.g., Forkuo and King, 2004; Seo et al., 2005; Arguilera et al., 2009; Böhm and Becker, 2007; Wang and Brenner, 2008; Weinmann et al., 2011). Dold and Brenner (2006) presented an automated registration method that extracts planar patches from two overlapping scans and finds the corresponding patch based on a search strategy. Moreover, the textures of corresponding patches are used to improve the registration process. Al-Manasir and Fraser (2006) incorporated the relative orientation of images and the relationship between the camera and TLS coordinate systems simultaneously to determine the exterior parameters of TLS stations. Barnea and Filin (2007) proposed a registration approach using a direct relationship between acquired images and laser data. In this method, calibration between the imagery and the laser scanner, finding the corresponding image points, and linking the laser scans and the image information must be done. Yang et al. (2011) used the standard SIFT detector to find the corresponding image points that will be used as tie points between the 3D structure-from-motion points and the scans. Then they used dominant planes extracted from the point clouds to achieve registration between different scans. Kang et al. (2009) built a panoramic reflectance image by projecting laser-scanned point clouds onto 2D images. This method simplifies the registration process and provides robust matching across a range of distortions, illumination changes, and noise additions. In addition, with the help of an

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http://dx.doi.org/10.1016/j.isprsjprs.2014.05.012

external sensor (e.g., a GPS receiver), the geographic coordinates of a terrestrial laser-scanning center can easily be measured to obtain relative spatial positions between multiple scans, and registration can thus be realized (e.g., Coveney and Fotheringham, 2011; Wang et al., 2011; Skaloud et al., 2010). Although registration tasks can be carried out with support from third-party data (e.g., imagery, intensity information), calibrating the camera and the scanner is clearly still a non-trivial issue. Moreover, image quality (e.g., distortion, illumination) and availability also have a direct effect on the registration process.

Many research groups have aimed to solve the registration problem without the support of third-party data (e.g., Jost and Hugli, 2002; Pottmann et al., 2006; Brenner et al., 2008; He et al., 2013). Johnson and Kang (1999) proposed a viewpoint-invariant surface representation called spin images to accomplish pairwise registration. However, the registration process is strongly affected by bin sizes, image widths, and support angles. Many studies have been carried out on registering different scans based on straight lines extracted from scans (e.g., Stamos and Leordeanu, 2003; Chen and Stamos, 2005). This kind of solution is valid for registering scans with abundant man-made objects (e.g., buildings, roads) where straight lines can easily be extracted. Feldmar and Ayache (1996) proposed a registration method based on the principal curvatures of neighboring points. However, the probability of wrongly matched point pairs is very high, leading to instability of registration tasks. Bae and Lichti (2004) used changes in geometric curvatures and normal vectors to perform registration tasks. Bae and Lichti (2008) derived the Cramer–Rao lower bound of registration error by considering position uncertainty. Then a random sample consensus (RANSAC) method was used to remove outliers based on position uncertainty. Other researchers have constructed shape descriptors to register points from different scans. Belongie et al. (2001) constructed a shape context descriptor with globally discriminative characterization to describe the log-polar histogram bins of each point. Then the registration process was completed by matching the histogram bins. Gruen and Akca (2005) applied the generalized Gauss-Markov model to parametric space-curve matching. The sum of squares of the Euclidean distances between the curves was minimized to obtain the transformation parameters based on the solid theory of least-squares matching. This method shows the potential opportunities of matching arbitrarily oriented 3D curves.

Generally, complex scenes (e.g., heritage sites) have multiple objects with free forms. Moreover, many objects may not be touched or moved and are large in volume, resulting in difficulties in data capture. Because of the limitations of complex scenes (e.g., occlusions), points captured at different sites have varying point densities and orientations and overlapping areas, leading to difficulties in robust registration, particularly for registration methods based on point, linear, or planar features which have difficulty finding correspondences between the points of freeform objects. Registering the scans of freeform surfaces based on their corresponding curves offers many advantages. On the one hand, curves are effective features to describe visually prominent and meaningful shape characteristics of complex objects (e.g., the Buddha). Moreover, curves can be distinguished accurately and robustly according to the principles of elastic mechanics (Mio et al., 2007), leading to reliable matching between corresponding curves. Inspired by this point, the authors extracted crest lines from scans and used them as invariant features for registration primitives. The next step was to construct a deformation energy model to describe the shape characteristics of the extracted crest lines according to the principles of elastic mechanics. The corresponding crest lines between scans were found using the strain-energy differences of the crest lines as measured by the deformation energy model, resulting in good initial orientation parameters between scans. Finally, fine registration was achieved using the ICP algorithm (Besl and McKay, 1992).

The rest of the paper is structured as follows: after the introduction, the process of extracting crest lines from scans is described in detail. Then construction of the deformation energy model using crest lines is described, and the process of finding corresponding crest lines to register scans is presented. Then the comprehensive experiments that were undertaken to demonstrate the validity and effectiveness of the proposed registration method are described. Finally, conclusions are presented in the last section.

2. Methodology

The proposed method encompasses three key components: extracting crest lines from laser scans, constructing the deformation energy model from the crest lines, and matching crest lines to achieve registration. Fig. 1 illustrates the framework of the proposed method.

2.1. Extracting crest lines from laser scans

The geometric curvature of the surface formed by a point indicates local shape changes. To calculate the geometric curvature of a point, the normal vector of the point is first estimated by the eigenvectors associated with the minimum eigenvalue of the covariance matrix of the point and its neighborhood. Thus, the surface formed by the points is obtained, and the parameter (U, V) of a point on the surface can be calculated, resulting in the quadratic surface of the point. Let the first and the second fundamental forms of the quadratic surface be < E, F, G > and < L, M, N > respectively. The Gaussian curvature K and the mean curvature H can be expressed as:

$$K = \frac{LN - M^2}{EG - F^2},$$

$$H = \frac{NE - 2MF + LG}{2(EG - F^2)}.$$

Hence, the principal curvature of one point can be written as:

$$\begin{aligned} k_1 &= H + \sqrt{H^2 - K} \\ k_2 &= H - \sqrt{H^2 - K} \end{aligned}. \tag{1}$$

Fig. 2 illustrates the principal curvature distribution of a scanned object.

Fig. 2 makes it clear that points with large geometric curvature indicate large changes in geometric shapes and represent many visually prominent linear features, among them the crest lines of surfaces, which are like the ridge lines of a digital elevation model (DEM). The points with large geometric curvature can be classified into a number of linear clusters. Then each linear cluster can be described in the form of one crest line. Let L be the degree of linear direction, $L = \lambda_1/\lambda_2, \lambda_1 > \lambda_2 > \lambda_3$, where $\lambda_1, \lambda_2, \lambda_3$ are the eigenvalues of one point. To cluster points of large geometric curvature to extract crest lines, the following steps are proposed to classify points of large geometric curvature into linear clusters.

Step 1: Select the point with the maximum degree of linear direction as the seed point of one linear cluster;

Step 2: Search for the potential cluster points of the current seed point in the sphere with a radius less than a threshold D (e.g., twice the average point span). Suppose that the angle between the principal direction of the seed point and one potential cluster point in the sphere is less than a threshold T_1. Each potential cluster point is added to