Image-Based Registration Method for Terrestrial Laser Scanner Data

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Key words: terrestrial laser scanning, 3D point cloud,registration, digital images, 3D similarity transformation

SUMMARY

The registration of point clouds forms the first task associated with building 3D models from laser scanner data in cases where multiple scans are required for complete coverage of the scene or object being recorded. This paper presents an image-based registration method for terrestrial laser scanner (TLS) data in which the transformation parameters of one data set with respect to another are determined via 3D similarity transformation. Digital images of the object are recorded using a calibrated digital camera, rigidly attached to the laser scanner. These images are used to identify, measure and label manually in the imagery from each TLS station feature points which can be served as common points between overlapping TLS data. The spatial position and orientation of the camera within the TLS coordinate system, along with the well known collinearity equation of close range photogrammetry, are then used to automatically find the feature points in the laser scanner point clouds. Finally, the identified feature points in the scan data serve as common or 'tie' points for the 3D similarity transformation which registers one point cloud with another overlapping data set. The proposed method provides a simultaneous registration of overlapping TLS point clouds. Test results obtained with the approach are presented to highlight its practicability and accuracy

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1. INTRODUCTION

The terrestrial laser scanner (TLS) is a line-of-sight instrument which can directly acquire dense 3D point clouds in a very short time. Given visibility constraints from single TLS stations, it is often necessary to combine multiple, overlapping point clouds into a single data set to fully cover the object being surveyed. The registration process involves determination of the transformation parameters between the local Cartesian coordinate reference systems of the overlapping point clouds such that all can be 'registered' in a common coordinate system.

Different methods have been developed to register 3D point clouds. The most popular method is the Iterative Closest Point (ICP) algorithm for surface matching (Besl and MacKay, 1992). The ICP process starts with the assumption that the two 3D data sets are in approximate registration, so one is effectively a subset of the other, with each point in one data set having a corresponding point in the other (Besl and MacKay, 1992 and Zhang, 1994). The orientation difference between the two sets is then iteratively reduced by matching a number of points on one surface with the closest points on the other surface and minimizing the sum of squares of the spatial offset distances.

Several improvements to the ICP algorithm have been made since its introduction. An ICP algorithm based on point-to-tangent plane has been used instead of point-to-nearest point distance as a registration function (Chen and Medioni, 1992), and a thresholding technique has been employed to control the maximum distance between points (Zhang, 1994). Also, the ICP algorithm has been extended to use Least Median of Squares with random sampling that is robust to a partially overlapping scene (Masuda and Yokoya, 1995) while using the sensor acquisition geometry have been suggested to search for correspondences between point clouds (Park and Subbarao, 2003).

The ICP method is computationally intensive and quite time consuming in its search for conjugate points in the two point clouds (Sequeira et al., 1999). It always converges monotonically to a local minimum with respect to the mean-square distance objective function (Besl and McKay, 1992). However, even in cases of good initial values for the transformation parameters, the ICP algorithm may converge to a wrong solution due to its closest point (or tangent plane) search scheme. The current 3D surface registration algorithms have been reviewed in several publications (Gruen and Akca, 2005).

A further approach for 3D scene registration is the Least Squares 3D Surface Matching (LS3D) (Gruen and Akca, 2005). The LS3D method is based on a minimisation of the sum of squares of the Euclidean distance between the different data sets. This approach assumes one point cloud as a reference and the other is iteratively transformed to it until an acceptable registration is achieved. The combined, co-registered data set can then be transformed to any reference system using control points. In order to accelerate the LS3D method, a fast correspondence search for 3D surface matching is suggested. The main shortcoming in the LS3D approach seems to be that it has small convergence radius, hence the need for good approximations (Gruen and Akca, 2005).

As illustrated by the Image-Based Registration (IBR) method for TLS point cloud registration proposed by (Al-Manasir and Fraser, 2006), imagery from a digital camera attached to the TLS can be used to provide a photogrammetric approach to point cloud registration. Images from the TLS-mounted digital camera are first used to relatively orient the network of images, after which the exterior orientation between TLS point clouds is determined based on the known relationship between the position and orientation of the camera and TLS. The IBR method can offer a one-step registration of multiple point clouds, with the exterior orientation being performed via a bundle adjustment. In instances where image identifiable features are used, the IBR registration can be fully automatic. A further advantage of the method is that it can achieve accurate registration even in instances where the TLS point clouds do not overlap. This means that data sets can be brought into a common XYZ-reference system without the need for any TLS tie points, though overlap between imagery is of course required. Moreover, the accuracy of the registration can be enhanced through the addition of extra images (without TLS data) in the bundle adjustment. An experimental evaluation of the IBR approach is reported in (Al-Manasir and Fraser, 2006).

In this paper the authors stay with the theme of employing a photogrammetry-based approach to TLS point cloud registration. Unlike the IBR method, however, the registration method described in this paper does not rely on relative orientation between images, though it does employ natural features which are recorded and manually measured within the images accompanying the TLS scans. From the image coordinates of the features and the known orientation and position of the camera with respect to the TLS, a vector to the feature can be generated in object space. This allows the 3D coordinates of the feature to be determined within the scanner point cloud, and thus provides a means of determining a set of potential 'tie' points for that point cloud. Registration with adjacent point clouds can then be carried out using the tie points to effect a 6- or 7-parameter Iterative Similarity Registration (ISR) (Al-Manasir, 2013). The proposed registration process displays practical advantages, though it doesn't come with the requirement to provide suitable, image-readable features.

2. THE REGISTRATION PROCESS

A brief overview of the registration process will initially be presented, after which a more detailed coverage of the separate stages is provided. A first requirement for the process is that the exterior orientation (rotation angles and translation components) of the calibrated camera with respect to the TLS coordinate system is known. This can be established via the well-known resection process in close range photogrammetry. A second requirement is that a sufficient number of suitable natural features on the object being surveyed can be selected such that, say, 5-8 of these will be common to adjacent scans.

The identification of the natural features in the imagery is constrained by the imaging scale and the feature size, smaller features always being preferred for practical reasons. Limitations in this area can be reduced somewhat by exploiting the zoom capabilities of the camera, though it is necessary to have the appropriate interior orientation and lens distortion parameters for each zoom setting employed. Each image may conceivably warrant a different zoom setting. The problem of varying calibration parameters with zoom setting has been circumvented in the proposed approach through use of so-called zoom-dependent calibration (Fraser and Al-Ajlouni, 2006), whereby the appropriate image coordinate corrections at any zoom setting are determined as a function of the lens focal length value recorded in the EXIF header of the image file.

After the image coordinates of the features are corrected for the principal point offset and radial lens distortion the collinearity condition and the exterior orientation of the camera within the TLS coordinate system are used to locate the features in the TLS point cloud. The located features then constitute potential tie points between adjacent scan data sets, and the provision of three or more such common points will facilitate the registration between two point clouds via 3D similarity transformation (Al-Manasir, 2013).

2.1 Image Coordinate Correction

Image measurements of features need to be first corrected for principal point offset and radial lens distortion. This is achieved via the zoom-dependent image coordinate correction model (Fraser and Al-Ajlouni, 2006) because different zoom settings will invariably be used for the different images. The correction model for zoom-dependent camera calibration is given as:

$$
\begin{aligned}
x^{corr} &= x - x_p^{(c_i)} + \left(x - x_p^{(c_i)}\right) K_1^{(c_i)} r^2 \\
y^{corr} &= y - y_p^{(c_i)} + \left(y - y_p^{(c_i)}\right) K_1^{(c_i)} r^2
\end{aligned}
\qquad (1)
$$

where

$$c_i = a_0 + a_1 f_i \qquad (2)$$

Here, f_i is the zoom focal length written to the EXIF header of the digital image, x,y are the measured coordinates and xcorr, ycorr the corrected image coordinates, c_i is the principal distance, $x_p^{(c_i)}$ and $y_p^{(c_i)}$ are principal point offsets, and $K_1^{(c_i)}$ is the coefficient of radial lens distortion.

2.2 Relationship Between the Camera and TLS Coordinate Systems

The determination of the relative position and orientation of the camera with respect to the TLS has been described by (Al-Manasir and Fraser, 2006) and here only a short summary of the process is presented. Following a separate camera calibration process, spatial resection from selected image-identifiable scan points is employed to determine the required rotation angles and 3-axis translations. Although a minimum of three object points is necessary for the spatial resection, 10 or so well distributed points would be recommended for accuracy and reliability reasons.

With the camera exterior orientation determined with respect to the TLS, transformation between the two Cartesian coordinate systems can be effected using the following well-known 3D conformal transformation model:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \lambda \mathbf{R}_C \begin{pmatrix} X - X^c \\ Y - Y^c \\ Z - Z^c \end{pmatrix} \qquad (3)$$

where (X, Y, Z) are the TLS point coordinates, the rotation matrix RC expresses the relative alignment between the axes of the two systems, and (X^c, Y^c, Z^c) expresses the position of the camera with respect to the origin of the TLS coordinate system. In this case the scale factor λ has unit value (unless a change of units is involved).

2.3 Feature Location in the TLS Point Cloud

Once all the features are manually identified in the imagery for each scan, they need to be identified in the object space, ie within the scanner point cloud. The well-known collinearity condition states that the perspective centre of the camera, the image point and the corresponding object point all lie along the same line, as illustrated in Figure 2 for the perspective centre, image point 'p' and corresponding object point 'P'. The direction of this line for a particular image point j is defined by the corrected image coordinates and principal distance, computed using Equations 1 and 2, as [x_j, y_j, c_i].

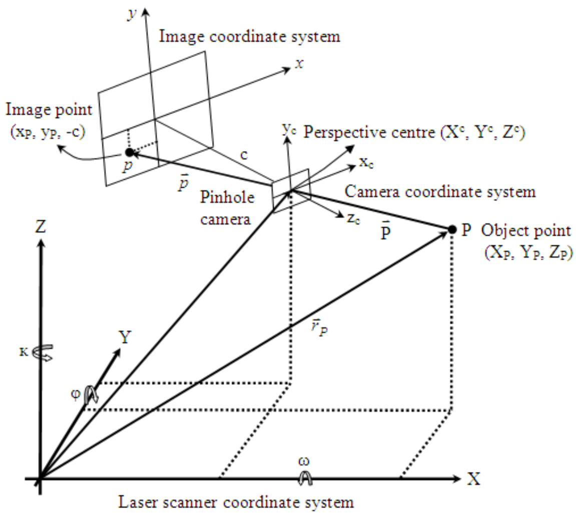

Figure 1.The geometric relationship between the camera and TLS coordinate systems.

In order to find the object point corresponding to a measured image point, the 3D coordinates of the TLS point cloud are first transformed into the image coordinate system. Then, for any feature in the image, the corresponding point in object space will be that lying closest to the imaging ray corresponding to the vector p. The mathematical relationship between the image and object point can be expressed as follows:

$$\vec{P} = \lambda \cdot \vec{p} \tag{4}$$

Since the scale factor for each individual image point is unknown due to the corresponding object point in the TLS not being known, a technique based on the collinearity condition is used to find the codes in the TLS point cloud.

The corresponding object space point for a feature point in the image space can be found as follows:

1. The scan data is transformed to a new coordinate system. The origin for the new system is the perspective centre of the camera as per Figure 2, with the z-axis passing through the vector p in the camera coordinate system. This transformation can be expressed as following:

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \mathbf{R}_T \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{5}$$

   Here, $[x, y, z]^T$ is as in Eq 3 and the matrix R^T is a 3x3 rotation matrix defining the camera rotations that allow the camera z-axis to pass through the vector p. R^T is computed as

$$R_T = R(\omega, \varphi, \kappa) \tag{6}$$

   where

$$\omega = \tan^{-1}\left(\frac{y}{|c|}\right)$$

$$\varphi = \tan^{-1}\left(\frac{-x}{|c|}\right)$$

$$\kappa = 0$$

   Here x, y are the corrected image coordinates for the feature and c is the corrected principal distance.

2. All scan points satisfying the following criteria are determined:

$$|x'| \leq \text{Threshold} \quad \text{and} \quad |y'| \leq \text{Threshold}$$

   The average spacing of the TLS points is used as the threshold value.

3. The result from the previous step is used to compute the centroid of all points. This

yields the object point corresponding to the image feature.

4. This correspondence determination between image measurement and TLS scan point is carried out for all the features, in all images.

2.4 Point Cloud Registration

Once all the features are automatically identified in the scan data, the registration between point clouds is achieved via the Iterative Similarity Registration (ISR) (Al-Manasir, 2013). This uses the matched XYZ coordinates from the scan data for the features, which constitute the common points between point clouds.

3. EXPERIMENTAL VALIDATION

Three experimental applications of the proposed method have been conducted using the Riegl LMS-Z210 and Lecia HDS7000. The first involved a typical task that might be undertaken with a LS, namely the 3D measurement and modelling of a heritage site. The second is the 3D modelling of the engineering building at Nottingham University Ningbo China.

The Riegl LMS-Z210 laser scanner can perform data acquisition at a range from 2 to 350 metres with accuracy in the range of ±25mm under normal conditions. While the Lecia HDS7000 can perform data acquisition at a range from 0.3 to 187 metres with accuracy in the range of ±1mm under normal conditions.

3.1 Cook's Cottage

In order to evaluate the practicability of the proposed method a field test was carried out in which Cook's Cottage, a heritage site and popular tourist attraction in Melbourne, was scanned from four stations with the Riegl scanner. The laser data comprised about 2 million points. Four images were recorded with the mounted Nikon D100 camera, one from each TLS station. Stations were selected to ensure that there would be sufficient overlap between images to support the registration of the TLS datasets. The geometry of the survey is indicated in Figure 2.

In the initial image measurement stage, all the features were manually identified in the imagery, and following the image coordinate correction and transformation of the TLS point cloud data into the image coordinate system (sequentially for each imaged feature via Equation 5), the 3D positions of features were determined in object space. The resulting 3D similarity transformation computations produced the final, registered 3D point cloud shown in Figure 3.

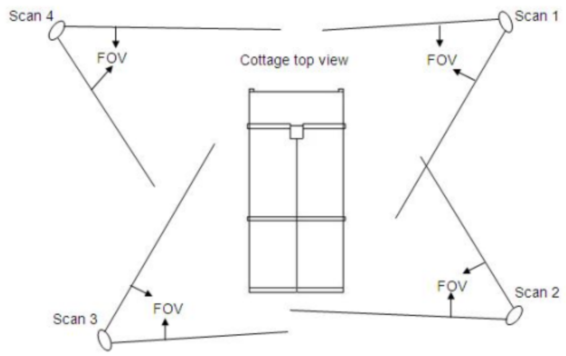

Figure 2: Scanner station geometry for the survey of Cook's cottage.

In order to check the accuracy of the registration approach the final 3D model was compared to one which had been generated via an ICP computation. The chosen ICP algorithm employed surface gradients to facilitate solution convergence to a global rather than local minimum. The ICP solution converges after 130 iterations.

A second ICP computation was then performed to assess the degree of alignment and shape correspondence between the two registered point clouds. The resulting RMS discrepancy between the closest points in the two models was 4.2mm. A visual analysis of the discrepancy vectors did not suggest the presence of any systematic misalignment between the two 3D models, which indicated that for all practical purposes the two solutions were equivalent.

Figure 3: The resulting laser scanned 3D model of Cooks' cottage.

3.2 Engineering Building at Nottingham University Ningbo China

In order to evaluate the practicability of the proposed method a second field test was carried out in which the engineering building at Nottingham University Ningbo China was scanned from four stations with the Lecia HDS7000 scanner. The laser data comprised about 10 million points.

Registration of the laser scans was then carried out using the proposed methods, with the resulting registered 3D point cloud being shown in Figure (4).

In order to check the accuracy of the registration approach the final 3D model was compared to one which had been generated via an ICP computation. The chosen ICP algorithm employed surface gradients to facilitate solution convergence to a global rather than local minimum. The ICP solution converges after 150 iterations.

A second ICP computation was then performed to assess the degree of alignment and shape correspondence between the two registered point clouds. The resulting RMS discrepancy between the closest points in the two models was 2.3mm. A visual analysis of the discrepancy vectors did not suggest the presence of any systematic misalignment between the two 3D models, which indicated that for all practical purposes the two solutions were equivalent.

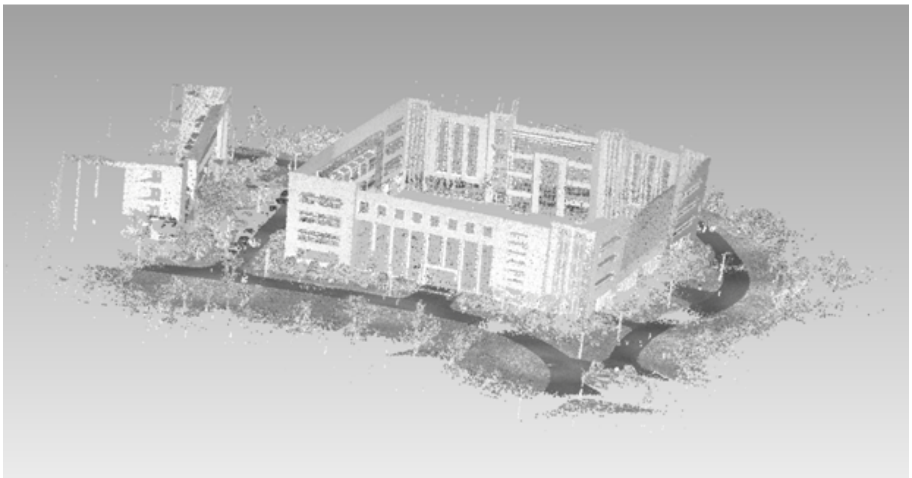

Figure 4: The resulting laser scanned 3D model of Engineering Building.

4. CONCLUSIONS

A registration method for terrestrial laser scanner data augmented with imagery from a camera mounted on the TLS has been presented. The proposed approach employs image-measured natural features coupled with 3D similarity transformation using the determined 3D positions of the features in the TLS point cloud.

The results of two test evaluations of the registration method have been presented. In the first test survey the 3D model formed via the proposed method was found to be in overall alignment with that obtained via an ICP registration to an RMSE of 4.2mm. While in the second test survey the 3D model formed via the proposed method was found to be in overall alignment with that obtained via an ICP registration to an RMSE of 2.3mm.

As a final comment, the image-measured feature registration method follows the same philosophy as in the IBR method previously developed by the authors, namely that photogrammetric processing of imagery from the digital cameras nowadays attached to TLS systems can provide a very useful means to assist and even enhance the TLS point cloud registration process.

REFERENCES

Al-Manasir, K. and Fraser, C.S., 2006, Registration of terrestrial laser scanner data using imagery, Photogrammetric Record, 21(115), 255-268.

Al-Manasir, K., 2013, “A fully automatic registration method for laser scanner data", Radar Conference, 1-6.

Besl, P.J. and McKay, N.D., 1992, A method for registration of 3-D shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence, 14(2), 239-256.

Chen, Y. and Medioni, G., 1992, Object modelling by registration of multiple range images. Image and Vision Computing, 10(3), 145-155.

Dold, C., 2005, Extended Gaussian images for the registration of terrestrial scan data. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 36 (3/W19), 180-186.

Fraser, C.S. and Al-Ajlouni, S., 2006, Zoom-dependent camera calibration in close-range photogrammetry. Photogrammetric Engineering and Remote Sensing, 72(9), 1017-1026.

Gruen, A.,Akca, D., 2005, Least squares 3D surface and curve matching. ISPRS Journal of Photogrammetry and Remote Sensing, 59(3), 151-174.

Ripperda, N. and Brenner, C., 2005, Marker-Free Registration of terrestrial laser scans using the Normal distribution transform. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 36 (5/W17) (on CD-Rom).

Zhang, Z., 1994, Iterative point matching for registration of free-form curves and surfaces. International Journal of Computer Vision, 13(2), 119-152.

BIOGRAPHICAL NOTES

Khalil joined the University of Nottingham, Ningbo, China (UNNC) in September 2012. Before joining UNNC, he worked as an Assistant Professor of Geomatics in Jordan from September 2009 to August 2012. He also served as laser scanning specialist and acting manager for aerial mapping at Limitless LLC. During his professional experience at Limtless, Khalil pursued hands-on experience in photogrammetric and Lidar systems. Khalil oversaw and provided direction for operation of integrated state-of-art airborne and terrestrial acquisition systems to produce complete, high accurate flight-to-product mapping and image services. Before that he was a Graduate Research Associate and then a Research Fellow at the University of Melbourne, Australia. While he was at the University of Melbourne he worked on several research projects, including research projects in digital photogrammetry and airborne laser scanning. Khalil also worked on a project to develop a real-time tracking algorithm for the National Aeronautics and Space Administration (NASA). Also he carried out a research project on evaluating the ability and efficiency to use Airborne laser scanning, Bathymetric data in conjunction with terrestrial LIDAR to create a continuous digital elevation model, seamlessly integrating land elevation and shallow water bathymetry for the Australian Government Department of Sustainability and Environment (DSE) in Victoria, Australia.

Khalil has what it takes to be an excellent mentor and a remarkable scholar and has many experiences in general accreditation in foreign and domestic institutions. He has both industrial experience, significant research and a remarkable lecturing experience in Engineering Surveying and Space Geodesy and he provided consultancy work to industry in Australia and the US. Khalil is a member of the Chartered Institution of Civil Engineering Surveyors (ICES).

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