AUTOMATIC REGISTRATION OF TERRESTRIAL POINT CLOUD USING PANORAMIC REFLECTANCE IMAGES

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ABSTRACT:

Much attention is paid to registration of terrestrial point clouds nowadays. Research is carried out towards improved efficiency and automation of the registration process. This paper reports a new approach for point clouds registration utilizing reflectance panoramic images. The approach follows a two-step procedure: pair-wise registration and global registrations. The pair-wise registration consists of image matching (pixel-to-pixel registration) and point clouds registration (point-to-point correspondence), provided the correspondence between image and point cloud (pixel-to-point) is known. The image matching process delivers corresponding points within the overlapping area of two images. These points are matched to their 3D equivalent points within the point clouds. False accepted correspondences are successfully removed by a geometric invariance check. An iterative least-square adjustment completes the pair wise registration. The global registration on all point clouds is obtained by a bundle adjustment using circularly self-closure constraint. The approach is tested with several data sets (indoor and outdoor scenes) acquired by the laser scanner FARO LS 880.

1. INTRODUCTION

Presently, laser scanning techniques are used in numerous areas, such as object modelling, 3D object recognition, 3D map construction and simultaneous localization and map building (SLAM). One of the largest problems in processing of laser scans is the registration of different point clouds. Commercial software typically uses separately scanned markers to help the identification corresponding points. Some vendors (e.g. Leica) have implemented algorithms (e.g. ICP (Besl et al, 1992)) allowing registering without markers but still the corresponding points have to be selected manually.

Presently, great effort is given to approaches based on segmentation of laser scan points and consequent matching of extracted features (Bae and Lichti, 2004; Mian et al., 2004; Rabbani and van den Heuvel, 2005). As discussed in (Dold and Brenner, 2006) the prevalent directions of normal vectors (of planar patches) along urban streets are mostly two, i.e. perpendicular to the facades (for the buildings) and to the streets. In this case the translation parameters are weakly determined, since two planar patches are insufficient to compute the respective angles. The rotation parameters can still be derived because it is not influenced by the lack of a third perpendicular plane.

The approach presented in this paper belongs to the group of image-based registration (IBR). In the last several years, many scanners have been equipped with image sensors. The 3D information captured by the laser scanner is complemented with digital image data. The generally higher resolution of optical images and the well-established image processing algorithms offer attractive possibilities for automatic alignment of point clouds. Many researchers have reported investigations in this area (Dold and Brenner, 2006; Al-Manasir and Fraser, 2006; Barnea and Filin, 2008).

Most of the approaches described above refer to pair wise registration of laser scans. However, many applications (architectural, environmental, medical), the object to be surveyed requires more than two scans. The chain of the scans can be a ring (e.g. statues, isolated buildings, squares) or a strip (e.g. building frontlines, coastlines, mines). The registration of more than two views is somewhat more difficult, because of the large nonlinear search space and the huge amount of raw data involved. There is currently not yet a consensus on the best approach for solving global registration. Many interesting and useful approaches towards this problem have been proposed in the recent past, e.g. Pulli, 1999; Williams and Bennamoun, 2000; Sharp et al., 2004.

This paper presents a new approach for automatic IBR which circumvents the need to carry out any point correspondence searching within terrestrial laser scan (TLS) data-sets. Compared to the preceding IBR methods, the novelty of this approach concerns the following aspects: 1) In most IBR approaches using optical images, a camera calibration and camera to scanner registration are required, both of which may be error prone. Our method avoids this problem by using the reflectance imagery which is created directly from scans; 2) Our approach is working with scans obtained from 360° TLS; 3) The image point correspondence and the computation of the rigid transformation parameters (RTPs) integrated into an iterative process which allows for an optimization of the registration; 4) For global registration, the circularly self-closure constraint are deduced to circumvent the influence of correspondence error and moreover achieve the global optimised result.

The proposed method comprises two parts, i.e. pair-wise registration and global registration. The next two sections present detail descriptions of them respectively. Section 4 shows the tests and discusses the results. The final section concludes on current problems and outlines further research.

2. PAIR WISE REGISTRATION

The proposed method consists of three general steps: extracting distinctive invariant features, identifying correspondences, pruning false correspondences by rigid geometric invariance. The last two steps are iterative by using computed transformation parameters between two point clouds behind the panoramic image pair, so that more new matches can be included for transformation parameters computation to reach predefined accuracy threshold. In this paper, the correspondence between image points (pixels) of two overlapping images is called *pixel-to-pixel*, the correspondence between image points and 3D points of a laser scan is *pixel-to-point*, and the correspondence between 3D points in two lasers scans is *point-to-point* correspondence.

The following sections explain in detail the algorithms used in the iterative process.

2.1 Pixel-to-pixel correspondence

Pixel-to-pixel correspondence is the most important and critical for the proposed method. As 360° reflectance images are used, the panoramic stereo pair doesn't simply follow the left-and-right pattern as well-know by regular images. Generally, it is quite difficult to make any assumption on the set of possible correspondences for a given feature point extracted by normal corner detectors. Therefore we use SIFT method (Lowe, 2004) as it can provide robust matching across a substantial range of affine distortion, change in 3D viewpoint, addition of noise, and change in illumination. SIFT has been previously used into IBR (e.g. Seo et al., 2005; Barnea and Filin, 2007), but we have implemented it for the first in case of panoramic reflectance imagery.

The description of the algorithm to extract distinctive invariant features the reader may consult Lowe, 2004. In this paper, matches are identified by the strategy presented in (Lowe, 2004) that finding the 2 nearest neighbors of each keypoint from the first image among those in the second image. A match is accepted if the ratio of the distance away from the closest neighbor to that away from the second closest one is less than a predefined threshold.

This approach may easily identify false matches from panoramic reflectance images covering buildings, as building facades are likely to have repetitive patterns. Consequently, the rigid geometric invariance derived from point cloud is used to prune false correspondences in the next step, point-to-point correspondence.

2.2 Point-to-point correspondence

In this section, a rigid geometric invariance is employed to detect and remove false correspondence.

2.2.1 Outlier detection:

In the local coordinate systems of different point clouds, Euclidean distance between each two corresponding point pairs is clearly invariant (Fig.1). Namely, if point *A* and *A'*, *B* and *B'*, *C* and *C'*, *D* and *D'* are corresponding points respectively, the distances between the points should equal (e.g. $S_{AB} = S_{A'B'}$).

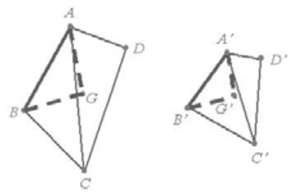


Fig.1 Distance invariance

Theoretically, it is possible to verify every two point pairs for distance invariance; however, this process may increase the computation time. To avoid this, we construct Delaunay Triangulated Irregular Network (TIN) and use the relations between the points in the triangles to decide on the distances. The 2D Delaunay triangulation is computed in the image plane and then mapped to the point cloud. Only those point pairs connected in TIN model will be verified for distance invariance.

As Fig.1, S_{AB} and $S_{A'B'}$ are practically impossible to be exactly equal thanks to the location errors of point *A* and *A'*, *B* and *B'*, which introduces the distance difference computed by Eq. (1). Therefore, we need to evaluate the tolerable error of the distance invariance. In (Barnea and Filin, 2008), this value is empirically acquired. However, as the distance invariance error is variant and related to each two corresponding pairs, the tolerable value should be self-adaptive and thus we evaluate it by the accuracy of the candidate points as follows.

$$\Delta S = \sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2} - \sqrt{(X_{A'} - X_{B'})^2 + (Y_{A'} - Y_{B'})^2 + (Z_{A'} - Z_{B'})^2} \quad (1)$$

X_i , Y_i , Z_i are the 3D coordinates of a point, where *i*, *i* designates *A* , *B*, *A'* and *B'* respectively.

Based on Eq. (1), the error of distance invariance $\sigma_{\Delta S}$ is estimated through error propagation law in light of the location error of each two corresponding point pairs.

According to the error propagation law, the variance matrix of point *i* is derived from the location error of point *i* which is determined by the laser scanner accuracy. Boehler (2003) mentioned the laser scanner accuracy consists of angular accuracy, range accuracy, resolution, edge effects and so on. As we know, angular and range accuracies are the main accuracy terms instrument claims, therefore, in this paper they are considered to estimate the location error. As the purpose herein is to evaluate the tolerable error of the distance invariance, instead of the investigation on systematic error models we just roughly use the specific accuracies the instrument claims and consider σ_R , σ_θ and σ_φ as invariant and independent for every point.

Three times of error of distance invariance is chosen as threshold to determine the correct correspondence and then Eq.

(1) can be written as:

$$|S_{AB} - S_{A'B'}| < 3\sigma_{\Delta S}$$

(2)Where, $\sigma_{\Delta S}$: Distance invariance error.

As Eq. (2), $\sigma_{\Delta S}$ is a variant and related to each two corresponding pairs, therefore the threshold chosen herein is self-adaptive instead of a constant. If the above condition is satisfied, those two point pairs are corresponding. Otherwise, there should be an outlier among those point pairs. According to Eq. (2), however, we cannot determine which point pair is an outlier or both of them are.

If the four point pairs in Fig.1 are corresponding respectively, the gravity point pair *G* and *G'* of those point pairs should be corresponding as well. Accordingly, we pick up the point pairs in agreement with Eq. (2) to compute the gravity point pair. The distances are computed between gravity point pair and those point pairs not satisfying Eq. (2). The outliers should be those point pairs which differences between corresponding distances are not smaller than $3\sigma_{\Delta S}$.

2.2.2 Computation of transformation parameters:

As well known, each single scan is registered into a local coordinate frame defined by the instrument. Using corresponding points detected at previous step, it is possible to compute transformation parameters between deferent coordinate frames and thus register the two point clouds. The least-square parameter adjustment for absolute orientation in photogrammetry is used to solve least-square optimized values of RTPs. Iterative process is implemented to acquire higher accuracy because error equations have been linearised.

It should be noticed that after the outlier detection, the wrong matched points are removed and RTPs are computed only with the correct ones. However, the outlier detection may remove many points so that the remained correspondences are unlikely to be uniformly distributed in the overlapping areas. Therefore, RTPs determined from them cannot be considered final. To be able to improve them, more points appropriate for matching have to be found. Therefore an iterative process is implemented.

2.2.3 Correspondence prediction:

Using the initial RTPs and inherent pixel-to-point correspondence, the feature points in the fixed reflectance image can be projected onto the unfixed one for the purpose of correspondence prediction. The image coordinates (*x'*, *y'*) corresponding to (*X'*, *Y'*, *Z'*) are certainly the expected position of corresponding point in unfixed image. Thereafter, a certain region centered at (*x'*, *y'*) is determined for tracking exact corresponding point. This practically means that more points from the extracted features points on the fixed image can be correctly matched. New values of RTPs are computed with the entire set of old and newly matched points.

This iterative process ensures matching of larger number of points and homogenous distribution of corresponding point, which leads to improved values of RTPs. The iterative process continues until the RMS error of transformation parameters computation satisfies a given threshold. This threshold is determined with respect to the angular and range accuracies of the scanner. This iterative process completes our procedure and the final RTPs are used to register two different point clouds.

3. GLOBAL REGISTRATION

The global registration of a long chain of scans can be seen as the problem of the photogrammetric triangulation of a single strip, which relies on the bundle adjustment of correspondences. Moreover, in many cases, one can logically design ring schemes for scanning targets and accordingly draw the closure constraint from it, which can be imposed in the bundle adjustment as a solution to the optimization, e.g. Zhai et al. (2006) proposed the bundle adjustment with closure constraint to implement seamless registration of multiple range images. Inspired by this work, our algorithm of global registration extends the closure constraint into a circular and self-closure form.

Zhai et al. (2006) formulized the closure constraint as below:

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = R_1 R_2 \cdots R_{m-1} \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} + \begin{bmatrix} T_{1,X} \\ T_{1,Y} \\ T_{1,Z} \end{bmatrix} + R_1 \begin{bmatrix} T_{2,X} \\ T_{2,Y} \\ T_{2,Z} \end{bmatrix} + R_1 R_2 \begin{bmatrix} T_{3,X} \\ T_{3,Y} \\ T_{3,Z} \end{bmatrix} + \cdots + R_1 R_2 \cdots R_{m-2} \begin{bmatrix} T_{m-1,X} \\ T_{m-1,Y} \\ T_{m-1,Z} \end{bmatrix} \tag{3}$$

Where, $\begin{bmatrix} T_{i,X} \\ T_{i,Y} \\ T_{i,Z} \end{bmatrix}$: Translation from scan *i*+1 to *i*; R_i : Rotation from *i*+1 to *i*.

Intuitively, point coordinates (X_m, Y_m, Z_m) in the last scan *m* is ideally transformed into corresponding (X_1, Y_1, Z_1) in the first scan using m-1 rigid transformations. The discord of this transformation process in practical terms is referred to as closure error. However, in the case of Eq. (3) it comprises not only transformation error, but also correspondence error which is not expected to reduce during the bundle adjustment. As a result, the closure constraint formulized by Eq. (3) is not errorless in ideal case.

To tackle this imperfection, we herein extend the closure constraint into a self-closure form. An extra transformation from S_1 to S_m is therefore computed out as ($R_{1\text{-}m}$, $T_{1\text{-}m}$) which enables the first scan S_1 self-closure and can be formulized as:

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = R_1 R_2 \cdots R_m \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} + \begin{bmatrix} T_{1,X} \\ T_{1,Y} \\ T_{1,Z} \end{bmatrix} + R_1 \begin{bmatrix} T_{2,X} \\ T_{2,Y} \\ T_{2,Z} \end{bmatrix} + R_1 R_2 \begin{bmatrix} T_{3,X} \\ T_{3,Y} \\ T_{3,Z} \end{bmatrix} + \cdots + R_1 R_2 \cdots R_{m-1} \begin{bmatrix} T_{m,X} \\ T_{m,Y} \\ T_{m,Z} \end{bmatrix} \tag{4}$$

Compared with Eq. (3), $\begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix}$ is replaced by $\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$ and accordingly one more transformation (R_m, T_m) is added, which means that after m rigid transformations $\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$ comes back to itself in ideal case, namely the closure constraint is errorless. In practical terms the closure error can reach least square after bundle adjustment as merely consisting of parameter errors. Besides, the self-closure form can be further extended to circular one as clearly transformation ring (($R_{2\text{-}1}$, $T_{2\text{-}1}$),…, ($R_{1\text{-m}}$, $T_{1\text{-m}}$)) allows each of the m scans to form a self closure. The bundle adjustment allows self-closure errors of all scans simultaneously reaching least square once circularly self-closure constraint is imposed in it. Multiple views registration holding true to this constraint will safely benefit from global optimization.

4. RESULTS

The approach is tested with several point clouds (indoor and outdoor scenes) acquired by FARO LS 880. The angular resolution selected for FARO LS 880 is 0.036° in both of horizontal and vertical directions. Dataset 1 is acquired for the office environment and Dataset 2 is scanned for outside buildings. The proposed method was implemented in C++. All the tests are performed on a PC with CPU Intel Pentium IV 3 GHZ and 1 GB RAM.

4.1 Pair wise registration

4.1.1 Indoor data set:

As presented in Section 2, SIFT method was used to extract distinctive invariant features from panoramic

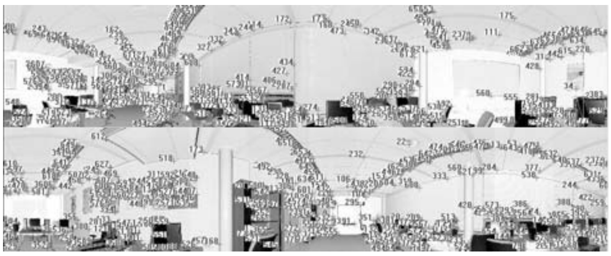


Fig.2 identified corresponding points

images and matches were identified from keypoints by looking for the descriptor vector with closest Euclidean distance. 655 corresponding point pairs were identified (Fig.2), however many are false accepted. The rigid geometric invariance derived from point cloud was accordingly used to prune false correspondences. Strict threshold was employed to ensure only correct matches can be remained. As a result, only 99 correct corresponding points (Partly illustrated as Fig.3) were kept against 655 shown in Fig.2. Trying to include more new matches, we used an iterative corresponding process to ensure matching of larger number of points and reasonable distribution of corresponding point. As Fig.4, 676 corresponding point pairs were acquired after iterative process and 99% of them are correct.

The registration of Dataset 1 was implemented with those correct corresponding points. The registration accuracy is 1.1mm after 2 iterations and average distance between corresponding points is 2.7mm. Both are the order of millimeter. The whole process of our method cost 5 minutes.

Fig.3 Corresponding points kept after pruning from Dataset 1

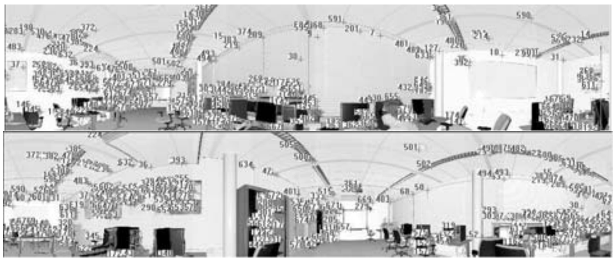


Fig.4 Corresponding points acquired after iterative corresponding process

4.1.2 Outdoor data set:

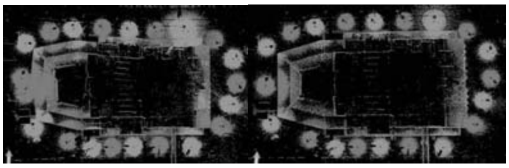
Dataset 2 consists of two point clouds of outside building. As Fig.5, the building facade has repetitive pattern, therefore, few corresponding points on the facade were kept after pruning false matches. By iterative matching process, plenty of correct corresponding point pairs on the facade were identified and the distribution of matches becomes homogenous in the panoramic images (Fig.6). The RMS of registration is 4.4mm and average distance between corresponding points is 4.8 mm. The whole process completed in 6 minutes after only 2 iterations.

Fig.5. Corresponding points kept after pruning from Dataset 2

Fig.6 Evenly distributed corresponding points on building façade

4.2 Global registration

Twenty full scans acquired the building of Aula of TU Delft were also employed to verify the three models. Fig.7 illustrates the registered point clouds before and after global registration. The error accumulation before global registration is visualized by the twisting building shape (the left part of Fig.7 (a)) and four pillars (highlighted in the rectangle in the right part of Fig.7 (b)) which are actually two. After the global registration, the twenty scans were perfectly registered through successfully eliminating the accumulated errors, as the right part of Fig.7.



a. Top views: before (left) and after (right) global registration
b.

b. Front views: before (left) and after (right) global registration
Fig.7 Registered real scans

5. CONCLUSIONS

In this paper, we have presented a fully automatic iterative registration method based on reflectance panoramic imagery which comprises the pair wise and global registrations. Several simulated and real data sets have been employed to test the proposed approach.

The tests with the reflectance panoramic images have shown that the registration accuracy is of millimetre order and the process is fully automatic and converges fast. Since the registration uses only the corresponding points obtained by image matching, the processing of the whole point cloud is avoided, which shortens the processing time remarkably. The experiment result of global registration on real data highlights that the bundle adjustment model imposed by the circularly self-closure constraint is undoubtedly able to harvest the global optimised result.

Our experiments have shown very promising results in most of the cases, but we foreseen further enhancements. Our next investigations will be towards more robust image matching algorithm and comprehensive description of distance invariance error, e.g. laser scanner accuracy aspects such as resolution, edge effects, incidence angle etc. should be taken into consideration.

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