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Automatic Registration of Terrestrial Scan Data based on Matching Corresponding Points from Reflectivity Images

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***Abstract*—In this paper, an algorithm is presented for automatic registration of terrestrial point clouds based on reflectivity images captured from terrestrial laser scanner. Firstly, the Moravec interest operator is used to extract feature points in the left one of two adjacent images and probabilistic relaxation is employed to match corresponding points for those feature points. The strategy of matching on image pyramid is used to improve the reliability and speed of image matching. Reflectivity images usually have low resolution, moreover, distinct geometric difference exits between adjacent images which are close-ranged. Consequently, the probability of erroneous matching becomes high. Therefore, geometric constraint (i.e. distance invariance) of 3D corresponding point pairs is used to eliminate erroneous corresponding point pairs. Iterative matching process is implemented to acquire high accuracy and stability. Thereafter, absolute orientation in photogrammetry is employed to compute six transformation parameters separated in rotation and translation. Experiments were implemented to testify the method, presented in this paper, on indoor and outdoor point clouds. Processes for those point clouds are fully automatic and acquire a good accuracy up to the order of millimeter.**

I. INTRODUCTION

As we know, one of the larges problems in processing of laser scans is the registration of different point clouds. Since the size of point clouds is usually pretty large, the commercial software typically uses separately scanned markers to solve the correspondence problem. Many research groups aim at improving the registration process of terrestrial laser scans and various matching algorithms without the need of artificial markers have already been proposed. A well-known method is ICP (*Iterative Closes Point*) algorithm [1] and thousand variants of it: ICCP (*Iterative Closest Compatible Point*) [2], ICPIF (*Iterative Closest Points using Invariant Features*) [3] etc. The basic idea of ICP is treating the nearest point in the other view as correspondent point. SVD (Singular Value Decomposition) is used to deduce the transformation matrix during iterative steps to align the scans to each other. The iterative solution is time-consuming and requires scans with considerable degree of overlap at the start position. If the models have insufficient overlap, ICP will converge to false result. Consequently, a good coarse matching is a precondition for a successful ICP.

Other reported methods are based on segmentation of laser scan points and consequent mating of extracted features. Features are derived from the point clouds and matched in a semi-automatic or automatic way. Bae and Lichti [4] have proposed a method for the registration of partially overlapping and unorganized point clouds using geometric primitives and neighborhood search. Liu and Hirzinger [5] have presented a marker-free automatic method for scan registering based on segmentation and interpretation tree. A combination of an interpretation tree and bipartite matching graph is used to conduct coarse matching to solve the pre-alignment problem. An efficient fine matching method, which is a variant of ICP, is employed to align the models accurately. Another registration algorithm divided in a coarse and fine matching stage is presented in [6]. Rabbani and Van den Heuvel [7] have presented a method for automatic point cloud registration by doing a constrained search for finding corresponding objects (such as planes, cylinders and spheres, which have been matched in the point clouds) and using them as targets. Feature-based methods perform well on relatively small data sets. When the size of point clouds becomes huge, e.g. scans for outdoor scenes, the computation time for calculating features increases remarkably and so does the demand for the capacity of RAM and graphic memory. Moreover, as mentioned in [8], a reliable determination of the parameters is possible, if the normal vectors of a triple of planar patches are perpendicular to each other. After extracting planar patches, the dominant directions of the normal vectors point to the directions across the streets and upright coming from the facades of houses and the ground. Due to the lack of characteristic planar patches where the normal vectors should point along the street, the transformation between different scan positions is underdetermined.

The approach presented in this paper is inspired by new developments in laser scan technology, i.e. a combination of geometric and radiometric sensors. In the last several years, many scanners are often combined with image sensors. The

3D information captured by the laser scanner instrument is complemented with digital image data. Because of the generally higher resolution, optical images offer new possibilities in the discrete processing of point clouds. Several researchers have reported investigations in this area [8, 9]. The reflectivity images are generated according to the angular coordinates and reflectivity value of every 3D point of point cloud. Usually the reflectivity image is used to get a photo-realistic impression of the scanned area. Since it is similar to a black and white photo and therefore does not require much experience to interpret, some applications of image matching and texture mapping, based on this kind of images, are carried out in traffic construction analysis [10] and tree species recognition [11].

The registration method proposed in this paper is a new approach and makes use of images to automate the point clouds registration. Because it acquires the corresponding points by image matching, the implement of whole point cloud is avoided which shorten the processing time remarkably and the registration process is fully automatic as well. Firstly correspondence points on the images are defined. These are identified within the corresponding scans and used for fully automatic registering of point clouds. Next section presents a detail description of the approach. Section III presents the tests and discusses the results. Section IV concludes on current problems and outlines further research.

II. Registration Method

The proposed method in this paper consists of three general steps: image matching, finding correspondence between image and point cloud scan and finally registration. 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. We assume that the pixel-to-point correspondence is known.

A. Registration process overview

Registration of data sets (images or point clouds) typically follows two steps: correspondence determination between two data sets and computation of the transformation parameters bringing one data set into alignment with the other. In this paper, the two steps are integrated as an iterative process.

To determine image matching (pixel-to-pixel correspondence) is implemented on reflectivity images. When image corresponding points are acquired, 3D corresponding points are picked out of the laser scans (on the basis of the known pixel-to-point correspondence). Some incorrect correspondences are possible because it is rather difficult to detect correct correspondences only from image information. In the step of blunder detection by distance invariance, rigid distance invariance is thereby employed to detect and remove those false correspondences. After blunder removal, transformation parameters are computed with 3D corresponding points. However, because of the large geometric distortion of corresponding points in the scans, it is always the case that most of corresponding points matched only on image information are in the region, which has smaller distortion. As a result, the transformation parameters computed are most likely imperfect. To tackle this problem, an iterative process is implemented to improve the matching accuracy and acquire reasonable distribution of corresponding point pairs. Using transformation parameters computed from previous matching, the positions of corresponding image points in the right image can be then better predicted and thus matched with more feature points extracted in left one. Corresponding points are matched again based on predicted positions with a smaller searching region and blunder detection is implemented afterwards. The iterative process continues till the transformation parameters reach predefined accuracy threshold.

The following sections explain in detail the algorithms used in the iterative process. Building image pyramid, point feature extraction and image correlation are processes related the pixel-to-pixel correspondence. The point-to-point correspondence refers to the blunder detection, computation of transformation parameters finding corresponding points and point cloud registering.

B. Pixel-to-pixel correspondence

The image matching algorithm, which is employed to find corresponding points between adjacent registered images, is explained bellow.

1) Image pyramid

Image pyramid (e.g. [12]) is usually used for the representation of a digital image in different resolution levels. It combines the advantages of both high and low resolutions of digital images without increasing the demand for disk space too much. The lower levels of an image pyramid provide detailed information, but a great amount of data, whereas the higher levels contain less information but give an overview and require a smaller amount of data. The strategy of coarse-to-fine matching on image pyramid is used to improve the reliability and speed of image matching. In each level, feature points are extracted using Moravec Operator in the left image.

2) Feature point extraction

Moravec operator (e.g. [12]) was developed by Hans P. Moravec in 1977 and is considered a corner detector since it defines interest points as points where there is a large intensity variation in every direction. Since feature points have small neighborhood, raw images are divided into grid. The size of grid cell is determined according to the resolution of images and normally larger than the size of searching window. In every grid cell, searching window is shifted by one pixel in each of the eight principle directions. Intensity difference for a given shift is computed. All potential feature points are picked out by threshold selected and the point with maximum difference among those points is determined as real feature points so that only one feature point extracted in each grid cell to ensure reasonable distribution of feature points.

After extraction feature points in left image, image correlation process is employed to match corresponding points in the right one.

3) Image correlation

Image correlation (e.g. [12, 13]) is a technique by which the conjugate point of a slave image (right) corresponding to the master image (left) is searched for the maximum correlation coefficient. The size of the window should be selected depending on the image resolution and feature size. 9 × 9 to 21 × 21 would be better used for digitized aerial photographs or close-range imagery.

C. Point-to-point Correspondence

After image matching process, corresponding point pairs are acquired in images. Since the pixel-to-point correspondence is known and organized in a file, the coordinates of corresponding 3D points can be searched out with respect to image coordinates. Normally, the average search complexity for each file is $O(\frac{mn}{2})$, where m is the number of corresponding image points and n is the size of point cloud. Because the large geometric distortion of corresponding features in closed-range registered imagery, some incorrect corresponding points are possibly accepted because image information is insufficient to detect them. Since registered imagery is already corresponded to point clouds, rigid geometric invariance is employed to detect and remove false correspondence.

1) Blunder detection by distance invariance

In the local coordinate systems of different point clouds, Euclidean distance between each two corresponding point pairs is undoubtedly invariant (Fig.1). Namely, if point *A* and *A'*, *B* and *B'* are corresponding points respectively, they should satisfy (1) under ideal condition.

$$S_{AB} = S_{A'B'} \tag{1}$$

Where, S_{AB} : Distance between point *A* and *B*;

$S_{A'B'}$: Distance between point *A'* and *B'*.

As Fig.1, two corresponding point pairs are needed to compute corresponding distances. It is theoretically possible to verify every two point pairs for distance invariance, however, this process will contribute to much computation and moreover it is not so necessary actually. In this paper, Triangulated Irregular Network (TIN) is constructed from scattered 3D points by X and Y coordinates based on Delaunay's triangulation. The TIN model is attractive because of its simplicity and economy and is a significant alternative to the regular raster of the GRID model. Delaunay triangulation is a proximal method that satisfies the requirement that a circle drawn through the three nodes of a triangle will contain no other node. The construction of TIN will not be emphasized in this paper. For detail please reference [14]. After construction of TIN model for 3D corresponding points, for each corresponding point pair only those point pairs connecting to it in TIN model will be verified for distance invariance with it. As a result, topology relation derived from TIN model is employed to reduce the complexity of distance invariance verification for all corresponding points.

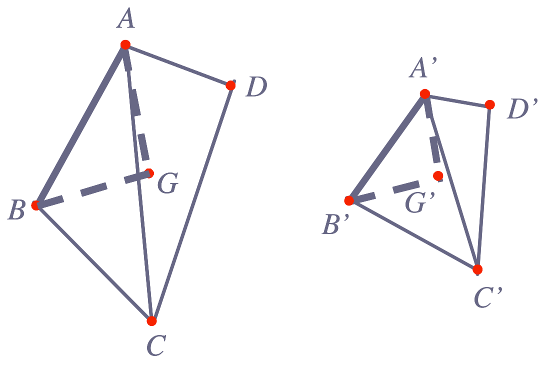


Figure 1. Distance invariance

Because of the location error, in fact, S_{AB} and $S_{A'B'}$ are impossible to be exactly equal. Therefore (1) is changed to (2).

$$\begin{aligned} Y_{DI} = &\sqrt{(X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2} - \\ &\sqrt{(X_{A'} - X_{B'})^2 + (Y_{A'} - Y_{B'})^2 + (Z_{A'} - Z_{B'})^2} \end{aligned} \tag{2}$$

Where, Y_{DI} : difference between corresponding distances;

X_i, Y_i, Z_i : the 3D coordinates of point *i*, *i* designates *A*, *B*, *A'* and *B'* respectively;

Based on (2), the error of distance invariance σ_{DI} is estimated by error propagation law (e.g. [15]) according to the location error of each two corresponding point pairs. The location error of point *i* is determined by the laser scanner accuracy. Boehler [16] 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, they are considered to estimate the location error.

Three times of error of distance invariance is chosen as threshold to determine the correct correspondence. Equation (1) can be written as:

$$|S_{AB} - S_{A'B'}| < 3\sigma_{DI} \tag{3}$$

Where, σ_{DI} : Distance invariance error.

Since σ_{DI} is a variant and related to each two corresponding pairs, therefore the threshold chosen here is self-adaptive instead of a constant. If the above condition is satisfied, those two point pairs are corresponding. Otherwise, there should be a blunder among those point pairs. According to (3), however, we cannot determine which point pair is a blunder 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 satisfying (3) to compute the gravity point pair. The distances are computed between gravity point pair and those point pairs not satisfying (3). The blunders should be those point pairs

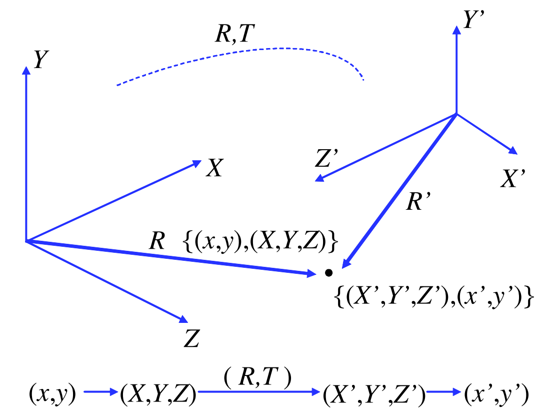


Figure 2. Initial position prediction

which differences between corresponding distances are not smaller than $3\sigma_{DI}$.

2) Computation of transformation parameters

The transformation parameters between deferent coordinate frames are computed with 3D corresponding points. The least-square parameter adjustment for absolute orientation in photogrammetry (e.g. [17]) is used to solve least-square optimized values of transformation parameters. Iterative process is implemented to acquire higher accuracy because error equations have been linearised. During the least-square parameter adjustment process, three times of RMS can be used as a criterion to detect outliers.

Owing to the large geometric distortion of corresponding features in closed-range registered imagery, usually most of corresponding points matched only based on image information are in the region has smaller distortion. The transformation parameters computed are most likely imperfect consequently. For optimization, an iterative process is implemented. Firstly, using transformation parameters computed from previous matching, the positions of corresponding image points in the right image can be predicted for current matching according to feature points extracted in left one.

3) Corresponding point prediction

When the transformation parameters are known, the position of corresponding points in the right image can be predicted because the image matching is usually based on the extracted feature points in the left image to search in the right one. As is illustrated in Fig. 2, based on image coordinate (*x*, *y*) of feature point in the left image, we can acquire the coordinate (*X*, *Y*, *Z*) of corresponding 3D point of left scan. Using transformation parameters, the coordinate (*X'*, *Y'*, *Z'*) in right scan can be calculated from (*X*, *Y*, *Z*). The image coordinate (*x'*, *y'*) corresponding to (*X'*, *Y'*, *Z'*) is certainly the predicted position of corresponding point in right image. Thereafter, a certain region centered at (*x'*, *y'*) is determined for searching exact corresponding point. Corresponding points were matched again based on predicted positions with a smaller searching region and blunder detection is implemented afterward.

There is no doubt that this prediction process can improve the stability and precision of image matching and acquire reasonable distribution of corresponding point pairs so that the accuracy of transformation parameters can be improved as well. The iterative process will be continued till the transformation parameters computed satisfy the accuracy demand.

After the iterative process, the transformation parameters computed are used to register the different point clouds.

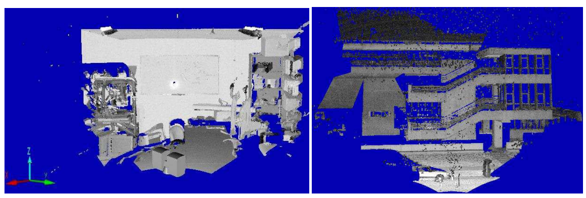
III. Experiments and Discussion

The approach presented in this paper is tested with two data sets (Fig. 3). Dataset 1 is acquired for the office environment and Dataset 2 is scanned for the building. The laser scanner employed is FARO LS. The angular resolution selected for FARO LS 880 is 0.036° in both of horizontal and vertical directions which is a quarter of full resolution the instrument claims. 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. In the paper, the distances between corresponding points were measured to evaluate the accuracy.

A. Indoor data set

In the reflectivity images of FARO LS 880 (Fig. 4), the pixel-to-point correspondence is straightforward and moreover there is no resolution difference between image and point cloud. Corresponding 3D points are readily available in the data file.

After the image matching, correct corresponding points are clustering in regions having relatively small geometric distortion, e.g. wall and bookcase (Fig. 4). In regions with large distortion (e.g. ceiling and the table), most of correspondence is false detected. The distance invariance was used to detect false correspondence based on TIN model. Since the image matching is based on feature points extracted in the left image, we regard the points in left image as fixed. Therefore the TIN model is constructed from 3D corresponding points only in left scans as shown in Fig. 5. Consequently, only those point pairs connected in TIN model will be verified for distance invariance. For instance, in Fig. 5 point *A* and its corresponding point in right image are only verified with point *B~I* and their corresponding point respectively. As a result, topology relation derived from TIN model is employed to reduce the complexity of distance invariance verification for all corresponding points.



a. Dataset 1 *b*. Dataset 2

Figure 3. Tested point clouds

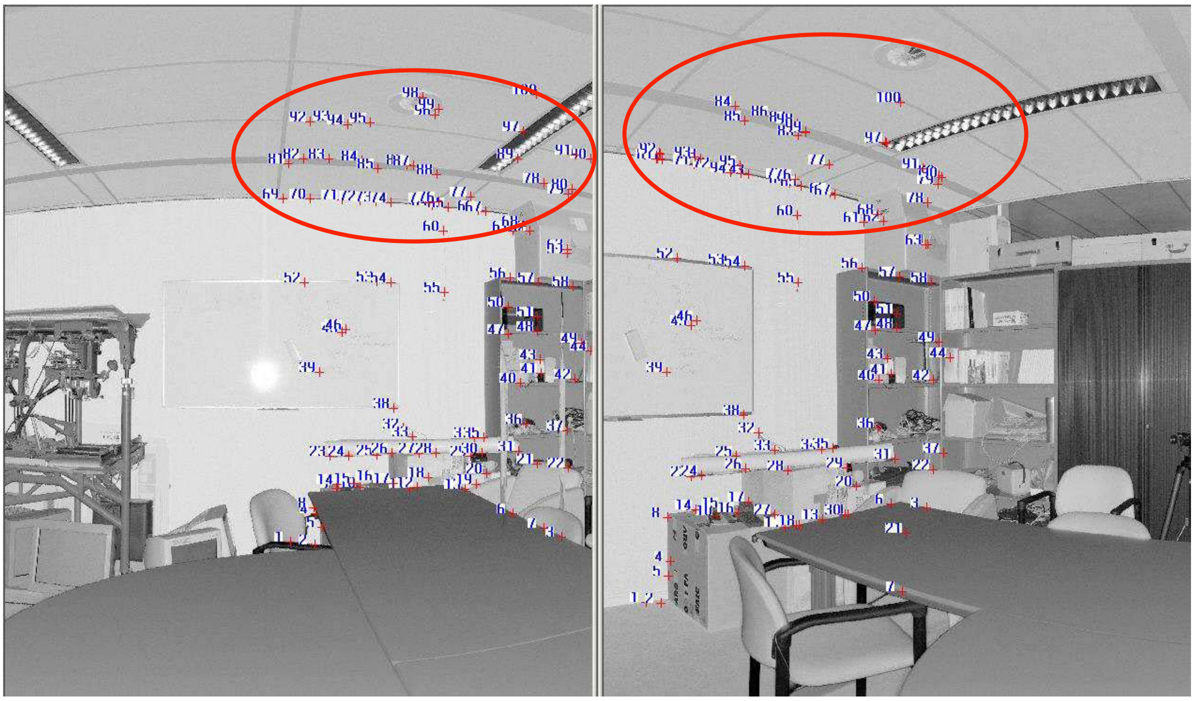


Figure 4. Matching result only based on image information for reflectivity image

In Fig. 4, 100 initial corresponding point pairs were matched only based on image information and we can see that most of the initial point pairs on the ceiling and table are false accepted. As we mentioned in previous section, $3\sigma_{DI}$, three times of error of distance invariance, is chosen as threshold to determine the correct correspondence. As listed in Table 1, the angular accuracy is 18µm+3µm/m and range accuracy is 3mm. According to them, the threshold for every judging of distance invariance is calculated using the range values and angular coordinates of each two corresponding pairs. The 3D corresponding in this paper is an iterative process. 3D corresponding points acquired were used to compute the initial transformation parameters between two different scans. As a result, the positions of corresponding image points in the right image were predicted by the parameters calculated and point-to-pixel correspondence. Corresponding points were matched again based on predicted positions with a smaller searching region. As shown in Fig. 4, most of point pairs (Highlighted in red circles) are erroneous corresponding. After iterative matching process, the matching for point pairs in red circle acquired good accuracies and totally 70 correct corresponding point pairs were kept (Fig. 6).

From the result we can see that correct corresponding points in previous matching are kept and false accepted correspondence in larger distortion regions is corrected to get a good matching accuracy by iterative matching process. The registration of Dataset 1 was implemented with those correct corresponding points. The registration accuracy is 6.3mm after 2 iterations and average distance between corresponding points is 8.5mm as shown in Table I. In Table I, n_i is the total

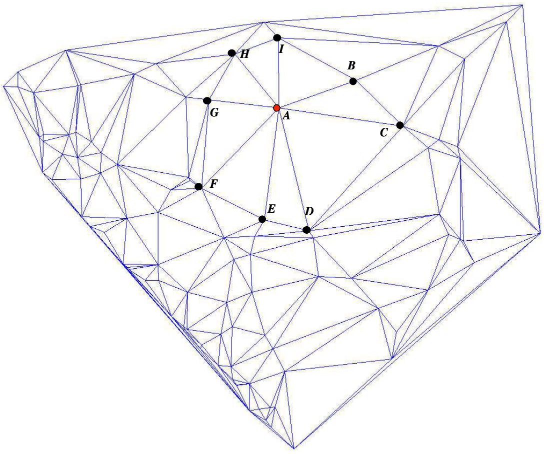


Figure 5. TIN models for initial 3D corresponding points, constructed for the left image

TABLE I. REGISTRATION RESULT (DATASET 1)

Dataset 1	n_1 n_2	i	RMS (m)	AVG (m)	Time (min)
Proposed method	2054987 2054987	2	0.0063	0.0085	0.5

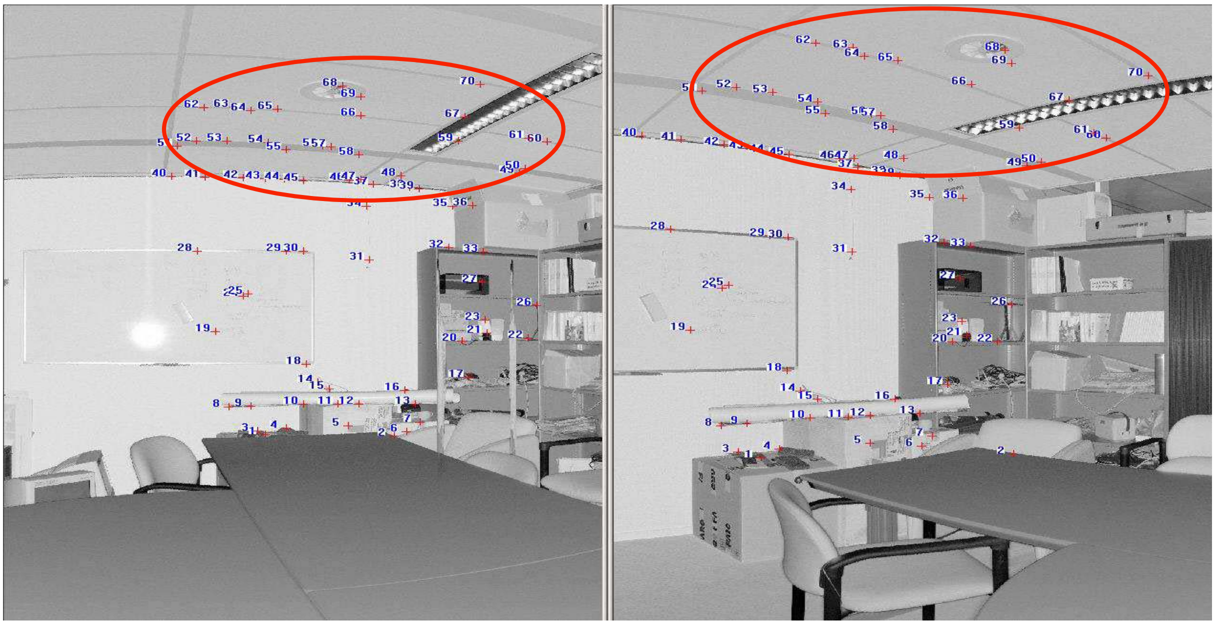
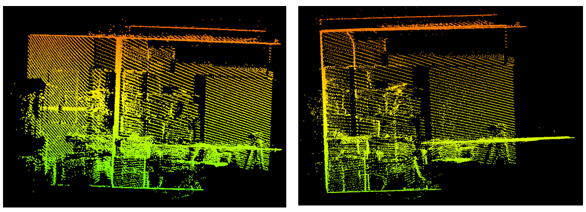


*Figure 6. The result after blunder removal (reflect*ivity image)

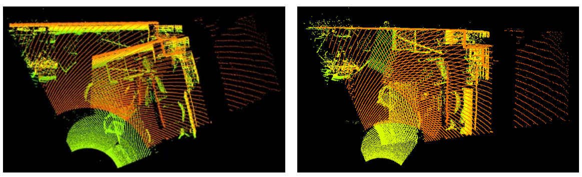
number of points of Dataset 1. *i* is the number of total iterations. RMS is the accuracy of registration. AVG is the average distance between corresponding points.Both are the order of millimeter. The whole process of our method cost only 0.5 minutes. Point clouds before and after registration are illustrated in Fig. 7. Point segments in the overlapping region of different scans are matched perfectly in the right part of Fig. 7.

B. Outdoor data set

Dataset 2 consists of two point clouds of outside building. By iterative matching process, 21 corresponding point pairs are matched (Fig. 8). The registration result is listed in Table II.



a. Side view: before (left) and after (right) registration



b. Top view: before (left) and after (right) registration

Figure 7. Registered Dataset 1

The RMS is 6.2mm and average distance between corresponding points is 13.2 mm close to the order of millimeter. The whole process completed in a very short time of 0.8 minutes after only 4 iterations. Fig. 9 shows the registered point cloud.

IV. SUMMARY AND OUTLOOK

In this paper, a fully automatic iterative registration method based on reflectivity imagery is presented and tested with several data sets. The approach consists of there basic processes: automatic pixel-to- pixel correspondence, known pixel-to-point registration and automatic point-to-point registration. Although at initial stage, the performed tests have exposed promising results and revealed several advantages compared to existing commercial software and reported research:

- It is a completely automatic process.
- It is applicable for any laser scanner that can output reflectivity images.
- Distance invariance and iterative point-to-point corresponding process allow for improving the registering accuracy.
- Since the method begins with image matching (always successful), the registration process should

TABLE II. REGISTRATION RESULT (DATASET 2)

Dataset 2	n_1 n_2	i	RMS (m)	AVG (m)	Time (min)
Proposed method	1785112 1716040	4	0.0088	0.0132	0.8

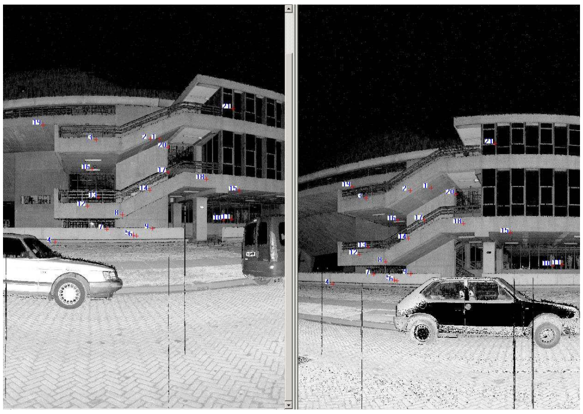


Figure 8. Corresponding points acquired from outdoor scene

be always possible.

Future work will concentrate on the issues given below.

- More aspects of laser scanner accuracy, e.g. resolution, edge effects, etc. should be considered to estimate the distance invariance error.
- The approach should be adapted to be able to deal with panoramic reflectivity imagery so that 360° full scans can be registered in a high efficient way and the number of stations for scan is certainly reduced remarkably.

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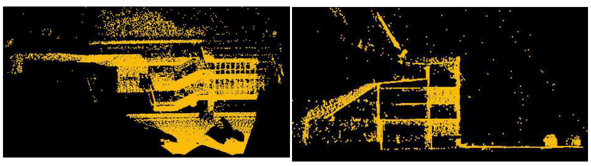

Figure 9. Registered Dataset 2

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