REGISTRATION OF AGIA SANMARINA LIDAR DATA USING SURFACE ELEMENTS

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ABSTRACT:

Several approaches for automatic registration of terrestrial LIDAR data exist. However, they normally can not be compared to each other because of a lack of reference data. This is especially true for applications in urban areas. One dataset available for this purpose is a set of eight LIDAR scans from Agia Sanmarina, a Byzantine church in Greece, which has been made available by the ISPRS working group V/3 on terrestrial laser scanning.
We have tested our plane based approach for automatic registration on this particular dataset: The point clouds are first split into a regular raster, then for each raster cell, the dominant plane is robustly estimated and denoted as surface element. Coarse registration is carried out via grouping the surface elements to large planes and a generate-and-test strategy to find transformation parameters that maximize the inlier count. Pairwise fine registration is accomplished using a variant of the ICP *(iterative closest point)* algorithm that is based on matching surface elements instead of 3D points. In addition to this, the theoretical framework for a simultaneous fine registration of multiple datasets is presented in this paper.

1 INTRODUCTION

The registration of terrestrial LIDAR data is a topic that is currently under discussion within the laser scanning community. Several approaches based on different assumptions have been proposed recently, but there is not yet an overall conclusion which method could be regarded as the best one. Recently published work includes, but is not limited to, (Akca, 2003, Dold and Brenner, 2006, Ripperda and Brenner, 2005, Rabbani and van den Heuvel, 2005, Wendt, 2004) and other publications cited later.

In general, registration of point clouds from LIDAR systems can be divided in two steps. The first step is the coarse registration where no information about the particular setup of the scan positions is known. The task here is to determine a set of initial transformation parameters that bring (typically) two datasets into a common geometric reference frame.

Then the fine registration follows as the second step. Here, it can already be assumed that the datasets are aligned sufficiently, i. e. within the convergence radius of the method. Fine registration refines the initial transformation parameters into an optimal parameter set, usually by minimizing the squared sum of the residuals of some error term.

Although a number of approaches exist for registration, this is not true for datasets as each group works on their own data. This is probably caused by a lack of suitable standard datasets. For the specific case of LIDAR data from urban areas, there is currently only a single dataset available from ISPRS Commission V. Despite the publications from the originating group (Bae, 2006), there have not yet been other known attempts to process the data.

In this paper, we will apply the plane based registration strategy from (von Hansen, 2006) to the Agia Sanmarina LIDAR dataset in order to determine its suitability. This method only contains the coarse registration step. We have already extended the approach by a fine registration based on the surface elements (von Hansen, 2007b) for the case of two datasets. Since the Agia Sanmarina data consists of eight datasets in a ring shaped topology, pairwise fine registration inevitably leads to contradictions. Therefore, we have extended the pairwise fine registration to a bundle adjustment style registration for multiple datasets.

This paper is organized as follows: The generation of surface elements, the coarse registration method and the pairwise fine registration will be briefly summarized in section 2. In section 3, the bundle adjustment based on surface elements will be formulated. Section 4 will shortly introduce the Agia Sanmarina dataset and show the results obtained on it. The paper will conclude with some remarks regarding both the dataset and the tested methods.

2 PREVIOUS WORK

This section will briefly summarize the work this paper is based on. The original idea for the replacement of the point cloud by surface elements and the coarse registration based thereupon has been taken from (von Hansen, 2006). The pairwise fine registration is taken from (von Hansen, 2007b).

2.1 Surface elements

The raw data acquired by a LIDAR system is a huge set of (sometimes millions of) 3D points. The disadvantage of this representation is that the points are not related to each other. Sometimes, the neighborhood of points is known from the scan geometry so that region growing can be used to extract object surfaces from the data (Dold and Brenner, 2004). In the generic case, the neighborhood information is not available so that the data must be processed as true point data.

One possibility to bring structure into the data are surface elements, i. e. local plane patches that approximate the object surfaces. They are generated by a two step process. First, the point cloud is divided into a regular 3D raster of a given raster size. The raster size should be chosen such that an object surface is spread among several of the 3D cells, leading to an over-segmentation of the scene. In the second step, a single plane is robustly estimated from all points of a raster cell via a RANSAC scheme. This plane called the *surface element* and shall be a replacement for all the points in the cell. This way, the millions of raw 3D points are replaced by – depending on the raster size – a few hundred or thousand small planes.

2.2 Coarse registration

For the coarse registration, the surface elements are first grouped to larger planes based on neighborhood in the 3D raster and coplanarity. This way, each planar object surface is represented by one plane.

If plane based coarse registration would be tackled in a conventional way, the algorithms would be extremely slow due to a combinatorial explosion as three matching planes must be found in order to compute all six parameters of a rigid transform without scale (Dold and Brenner, 2004). The barycenter of a pair of matching planes can be used to compute the translation so that only two matches are required for the unknown rotation (He et al., 2005). (von Hansen, 2006) goes even further by assuming parallel zenith directions of two scan positions, thereby allowing to recover the transformation parameters from a single pair of matching planes only. A pre-rotation carried out separately for each dataset as shown in (von Hansen, 2007a) makes this approach suitable for generic sensor setups that include arbitrary rotations.

In this particular case, a complete search can be used to find the correct parameters: For each possible match, the transformation parameters are computed and a high number of inliers, planes matching for a given transformation, determines the correct transformation. This technique is fast for a small number of planes – up to a few hundred on modern hardware – but it should be noted that more elaborate search techniques have been proposed as well (He et al., 2005, Liu and Hirzinger, 2005).

2.3 Pairwise fine registration

The fine registration based on surface elements uses a variant of the well known ICP *(iterative closest point)* algorithm (Besl and McKay, 1992). This consists of two alternating steps that are repeated until convergence.

The first step transforms the data using initial transformation parameters – those returned by the coarse registration for the first run and the updated parameters for all consecutive runs. Then, matching pairs of surface elements are found on a nearest neighbor basis.

In the second step, the transformation parameters are updated by a least squares adjustment minimizing the residuals between the matching surface elements. For the mathematical model for the pairwise registration one dataset is kept fixed while the other is transformed. The bundle adjustment presented in section 3 extends this approach to a more general formulation.

Convergence can be determined by observing the pair matches. If they remain unchanged, then a stable solution has been found. However, sometimes the iteration procedure is cycling through a number of solutions because each set of matches leads to a slightly different parameter set that in turn leads to a set of slightly different matches. In this case, some attenuation must be introduced. This had be done by changing the matching of surface elements in the first step. Instead of starting from scratch for each iteration, only those matches whose distance is above a certain threshold are reassigned to new partners.

3 BUNDLE ADJUSTMENT

Introduction This is an extension of the pairwise fine registration method shown in (von Hansen, 2007b). Opposed to the previous formulation where one dataset was kept fixed, the method

Figure 1. Agia Sanmarina and the Cyrax laser scanner. (By courtesy of ISPRS WG V/3)

as presented here can deal with multiple datasets in a free network. On the other hand, no ICP iterations are used, but a fixed set of input matches taken from the output of the pairwise registration.

This method will be called *bundle adjustment* here in reference to the idea of photogrammetric bundle adjustment even though LIDAR point clouds do not represent bundles in the strict sense.

Input data As input, the bundle adjustment relies on the output of a pairwise registration, requiring both the initial transformation parameters and the list of matching surface elements.

The first step is to determine initial transformation parameters for all datasets in a common reference frame. One dataset is used as starting point and, based on known relative registrations between datasets, all other datasets are subsequently added. Each of the n datasets is now given as a tuple

$$\mathcal{S}_i = (\mathbf{R}_i, \mathbf{t}_i, \mathcal{P}_i), \quad i = 1 \dots n \tag{1}$$

where $\mathbf{R}_i$ is the rotation matrix, $\mathbf{t}_i$ the translation vector and $\mathcal{P}_i$ the set of surface elements. A surface element

$$\mathbf{p} \in \mathcal{P} = (\mathbf{n}, \mathbf{x}) \tag{2}$$

is given by normal vector $\mathbf{n}$ and barycenter $\mathbf{x}$ that uniquely define a plane using the Hesse normal form

$$\mathbf{n}^\top \mathbf{x} - d = 0 \tag{3}$$

In addition there exists a set of matching surface elements

$$\mathcal{M} = \{(\mathbf{p}_i, \mathbf{p}_j), \mathbf{p}_i \in \mathcal{P}_i, \mathbf{p}_j \in \mathcal{P}_j\} \tag{4}$$

Vector notation for differential rotations For simplification, the datasets are transformed via the initial transformation parameters prior to the least squares adjustment. We will assume in the remainder, that these pre-transformations have been carried out implicitly. Therefore, one can assume the identity matrix as initial rotation ($\mathbf{R}_0 = \mathbf{I}$) and the null vector as initial translation ($\mathbf{t}_0 = \mathbf{0}$). The matrix for the differential rotation around angles α, β and γ is defined as

$$\mathbf{R} = \begin{pmatrix} 1 & -\gamma & \beta \\ \gamma & 1 & -\alpha \\ -\beta & \alpha & 1 \end{pmatrix}, \quad |\alpha|, |\beta|, |\gamma| \ll 1 \tag{5}$$

One can easily verify that

$$\mathbf{R}\mathbf{x} = \mathbf{r} \times \mathbf{x} + \mathbf{x}, \quad \mathbf{r} := (\alpha, \beta, \gamma)^\top \tag{6}$$

holds. This provides an easier way to write rotations for small angles using only vectors. Also, similar to $\mathbf{t}$, the initial rotation $\mathbf{r}$ is a null vector ($\mathbf{r}_0 = \mathbf{0}$).

Matching constraints In the remainder, indices 1 and 2 will be used to denote two input datasets. Each match $\mathbf{m}_i \in \mathcal{M}$ of two surface elements will lead to three constraints. As all datasets are treated similarly, this easily extends to any number of input datasets. Each surface element $(\mathbf{n}, \mathbf{x})$ is transformed via the (unknown) parameters $\mathbf{r}, \mathbf{t}$ to its ideal position $(\mathbf{n}', \mathbf{x}')$:

$$\mathbf{n}' := \mathbf{r} \times \mathbf{n} + \mathbf{n}, \quad \mathbf{x}' := \mathbf{r} \times \mathbf{x} + \mathbf{x} + \mathbf{t} \tag{7}$$

For an ideal solution a pair of transformed surface elements must be coplanar

$$\mathbf{n}_1'^\top \mathbf{n}_2' - 1 = 0 \tag{8}$$
$$\mathbf{n}_1'^\top \mathbf{x}_2' = d_1' = \mathbf{n}_1'^\top \mathbf{x}_1' \Leftrightarrow \mathbf{n}_1'^\top (\mathbf{x}_2' - \mathbf{x}_1') = 0 \tag{9}$$
$$\mathbf{n}_2'^\top \mathbf{x}_1' = d_2' = \mathbf{n}_2'^\top \mathbf{x}_2' \Leftrightarrow \mathbf{n}_2'^\top (\mathbf{x}_2' - \mathbf{x}_1') = 0 \tag{10}$$

i. e. the normal vectors are parallel (Eq. 8) and each barycenter lies on the corresponding plane (Eqs. 9/10). Using Eq. 7, Eqs. 8 to 10 transform to the conditions

$$\begin{aligned} C_1 = \; & \mathbf{r}_1^\top \mathbf{r}_2 \cdot \mathbf{n}_1^\top \mathbf{n}_2 - \mathbf{r}_1^\top \mathbf{n}_2 \cdot \mathbf{n}_1^\top \mathbf{r}_2 + [\mathbf{r}_1, \mathbf{n}_1, \mathbf{n}_2] + \\ & [\mathbf{r}_2, \mathbf{n}_2, \mathbf{n}_1] + \mathbf{n}_1^\top \mathbf{n}_2 - 1 = 0 \qquad (11) \\ C_2 = \; & \mathbf{r}_1^\top \mathbf{r}_2 \cdot \mathbf{n}_1^\top \mathbf{x}_2 - \mathbf{r}_1^\top \mathbf{x}_2 \cdot \mathbf{n}_1^\top \mathbf{r}_2 + [\mathbf{r}_1, \mathbf{n}_1, \mathbf{x}_2] + \\ & [\mathbf{r}_1, \mathbf{n}_1, \mathbf{t}_2] - \mathbf{r}_1^\top \mathbf{r}_1 \cdot \mathbf{n}_1^\top \mathbf{x}_1 + \mathbf{r}_1^\top \mathbf{x}_1 \cdot \mathbf{n}_1^\top \mathbf{r}_1 + \\ & [\mathbf{r}_1, \mathbf{t}_1, \mathbf{n}_1] + [\mathbf{r}_2, \mathbf{x}_2, \mathbf{n}_1] + \mathbf{n}_1^\top \mathbf{x}_2 + \mathbf{n}_1^\top \mathbf{t}_2 - \\ & \mathbf{n}_1^\top \mathbf{x}_1 - \mathbf{n}_1^\top \mathbf{t}_1 = 0 \qquad (12) \\ C_3 = \; & \mathbf{r}_2^\top \mathbf{r}_2 \cdot \mathbf{n}_2^\top \mathbf{x}_2 - \mathbf{r}_2^\top \mathbf{x}_2 \cdot \mathbf{n}_2^\top \mathbf{r}_2 + [\mathbf{r}_2, \mathbf{n}_2, \mathbf{t}_2] - \\ & \mathbf{r}_2^\top \mathbf{r}_1 \cdot \mathbf{n}_2^\top \mathbf{x}_1 + \mathbf{r}_2^\top \mathbf{x}_1 \cdot \mathbf{n}_2^\top \mathbf{r}_1 + [\mathbf{r}_2, \mathbf{x}_1, \mathbf{n}_2] + \\ & [\mathbf{r}_2, \mathbf{t}_1, \mathbf{n}_2] + \mathbf{n}_2^\top \mathbf{x}_2 + \mathbf{n}_2^\top \mathbf{t}_2 + [\mathbf{r}_1, \mathbf{n}_2, \mathbf{x}_1] - \\ & \mathbf{n}_2^\top \mathbf{x}_1 - \mathbf{n}_2^\top \mathbf{t}_1 = 0 \qquad (13) \end{aligned}$$

where $[\mathbf{a}, \mathbf{b}, \mathbf{c}]$ denotes the triple product $(\mathbf{a} \times \mathbf{b})^\top \mathbf{c}$. Note that most terms cancel out because $\mathbf{r}_i = \mathbf{t}_i = \mathbf{0}$. This longer form of the constraints is only needed for proper linearization of the least squares adjustment.

Constraints and derivatives Eqs. 11 to 13 are an implicit representation of the conditions and can be used for least squares adjustment using the Gauss-Helmert model (McGlone et al., 2004). For this model, we require the equations of the constraints and the derivatives with respect to parameters and measurements. The constraints are directly available by removing all terms containing $\mathbf{r}_i$ or $\mathbf{t}_i$ because they have the null vector as initial values:

$$C_1 = \mathbf{n}_2^\top \mathbf{n}_1 - 1 = 0 \tag{14}$$
$$C_2 = \mathbf{n}_1^\top (\mathbf{x}_2 - \mathbf{x}_1) = 0 \tag{15}$$
$$C_3 = \mathbf{n}_2^\top (\mathbf{x}_2 - \mathbf{x}_1) = 0 \tag{16}$$

Note that the constraints are similar to Eqs. 8–10, which is obvious as the initial values assume that both datasets already are at their optimal position. The derivatives are

$$\begin{aligned} \mathrm{d}C_1 = \; & (\mathbf{n}_1 \times \mathbf{n}_2)^\top \mathrm{d}\mathbf{r}_1 + (\mathbf{n}_2 \times \mathbf{n}_1)^\top \mathrm{d}\mathbf{r}_2 \\ & + \mathbf{n}_2^\top \mathrm{d}\mathbf{n}_1 + \mathbf{n}_1^\top \mathrm{d}\mathbf{n}_2 \qquad (17) \\ \mathrm{d}C_2 = \; & (\mathbf{n}_1 \times \mathbf{x}_2)^\top \mathrm{d}\mathbf{r}_1 - \mathbf{n}_1^\top \mathrm{d}\mathbf{t}_1 \\ & + (\mathbf{x}_2 \times \mathbf{n}_1)^\top \mathrm{d}\mathbf{r}_2 + \mathbf{n}_1^\top \mathrm{d}\mathbf{t}_2 \\ & + (\mathbf{x}_2 - \mathbf{x}_1)^\top \mathrm{d}\mathbf{n}_1 - \mathbf{n}_1^\top \mathrm{d}\mathbf{x}_1 + \mathbf{n}_1^\top \mathrm{d}\mathbf{x}_2 \qquad (18) \\ \mathrm{d}C_3 = \; & (\mathbf{n}_2 \times \mathbf{x}_1)^\top \mathrm{d}\mathbf{r}_1 - \mathbf{n}_2^\top \mathrm{d}\mathbf{t}_1 \\ & + (\mathbf{x}_1 \times \mathbf{n}_2)^\top \mathrm{d}\mathbf{r}_2 + \mathbf{n}_2^\top \mathrm{d}\mathbf{t}_2 \\ & + (\mathbf{x}_2 - \mathbf{x}_1)^\top \mathrm{d}\mathbf{n}_2 - \mathbf{n}_2^\top \mathrm{d}\mathbf{x}_1 + \mathbf{n}_2^\top \mathrm{d}\mathbf{x}_2 \qquad (19) \end{aligned}$$

Position	#elements	#planes
East	1250	50
Northeast	1917	79
North	1361	56
Northwest	4161	112
West	2339	75
Southwest	2547	82
South	1529	63
Southeast	2729	72

Table 1. Number of surface elements and large planes for each dataset.

Least squares adjustment Eqs. 14 to 19 can be used in a Gauss-Helmert model to solve for all unknown parameters $\mathbf{r}_i$ and $\mathbf{t}_i$. The measurements are the plane parameters $\mathbf{n}_{ij}$ and $\mathbf{x}_{ij}$ of the surface elements.

It should be noted that the equation system defined the way shown here will be singular with a rank defect of 6. This is due to an overall rigid transformation (rotation, translation) that could be performed without changing the constraints. For this reason, the bundle adjustment as shown here is a free adjustment. In order to solve the equation system, one can compute the pseudo inverse using the singular value decomposition and the explicit knowledge of the rank defect.

4 EXPERIMENTS

4.1 Dataset

The purpose of this work is to test the surface element based registration approach on a standard dataset containing buildings. We have chosen the Agia Sanmarina data which is published by ISPRS working group V/3 on terrestrial laser scanning (ISPRS WG V/3, 2004). Agia Sanmarina is a Byzantine church near Kalamata in Greece and is approx. $10 \times 20 \times 15\,\mathrm{m}^3$ in size. The scanner used was a Cyrax Cyra 2500. Both the church and the laser scanner are shown in Fig. 1.

There are eight datasets positioned around the church in $45°$ steps. Each dataset contains between 500 and 800 thousand 3D points. The opening angle of the scanner is rather small, so that the church fills most of the field of view. The object itself has many small and often highly structured surfaces which make it rather difficult for a plane based approach. Furthermore, it is difficult to find sufficient overlapping areas because the scanner has been positioned directly in front of one of the facades half of the time.

4.2 Generation of surface elements

The generation of the surface elements is straightforward and quite fast because the number of points is low compared to other laser scanners. Difficulties arose with the highly structured facades of the church because they are composed from many individual but small planes. The raster size of the 3D grid therefore had to be chosen rather small in order to get enough surface elements per object plane. On the other hand, the low point density

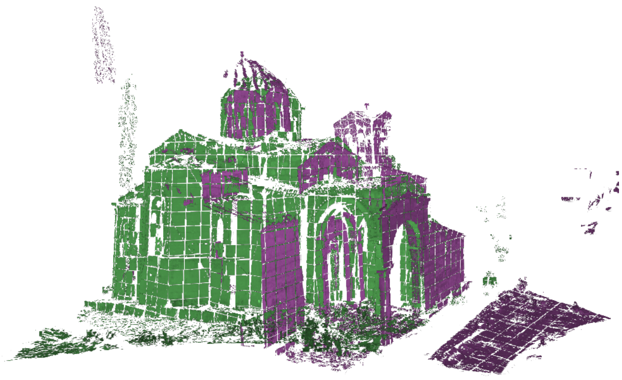

Figure 2. Coarse registration result for Northeast (green) and North (purple) positions.

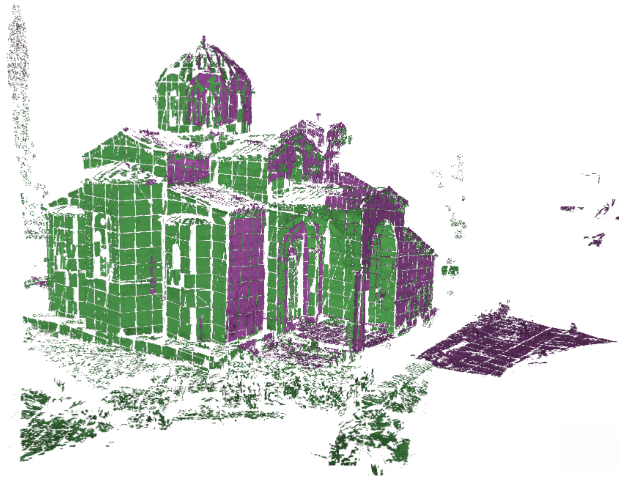

Figure 3. Fine registration result for Northeast (green) and North (purple) positions.

on the church – the nominal sampling interval is given as 1 cm at 10 m distance – did not allow too small surface elements. The best compromise was a raster size of 0.5 m. The number of generated surface elements ranges roughly from 1200 to 4200 depending on scene complexity (see Tab. 1). Examples of the surface elements can be seen in Fig. 2 as the little square structures.

4.3 Coarse registration

The first step is the generation of large planes from the surface elements. Tab. 1 lists their number which ranges from 50 to 112. Too small planes below five surface elements have been dropped in order to eliminate noise. The coarse registration required careful choice of the algorithm's thresholds so that all eight neighboring positions could be processed successfully.

Basically it can be reported that the plane based automatic coarse registration works for the Agia Sanmarina dataset. The main reason for the success is that two neighboring positions contain a common facade completely so that there is a chance for the algorithm to generate correct transformation parameters. Difficulties arose because correct parameters are only accepted if they are supported by a number of other planes matches and besides the common facade, almost no other features overlap.

Another possible source for errors is the tilted sensor as the coarse registration algorithm assumes parallel zenith directions. Even though this influence is visible in the coarse registration result (see Fig. 2) it did not prevent the extraction of a valid solution.

	$\alpha/°$	$\beta/°$	$\gamma/°$	x/m	y/m	z/m
Northeast	-6.4924	-1.1389	42.9209	-2.2892	15.6731	-0.3365
Southeast	3.7317	-1.1302	-28.8213	0.6569	-12.2696	0.1418
South	8.1701	-4.2542	-67.5171	-13.4374	-21.9461	-1.7592
Southwest	1.4909	-10.1123	-114.2456	-32.1951	-23.1324	-3.0601
West	-0.2914	-5.3232	-166.7708	-43.9244	-6.4330	-4.0994
Northwest	-1.7984	-9.5814	155.9213	-49.6421	9.6286	-5.2051
North	0.0711	-13.0660	91.4302	-20.8192	18.4335	-1.8945

Table 2. Resulting transformation parameters after bundle adjustment. They have been transformed such that the parameters for the East position are the identity transform ($\mathbf{r} = \mathbf{t} = 0$).

	$\Delta\alpha/°$	$\Delta\beta/°$	$\Delta\gamma/°$	$\Delta x/\mathrm{m}$	$\Delta y/\mathrm{m}$	$\Delta z/\mathrm{m}$
Northeast	0.24	-0.17	0.13	0.09	0.06	0.06
Southeast	-0.72	-0.55	-0.19	-0.10	-0.09	0.23
South	-0.30	-0.86	-0.46	-0.25	-0.14	0.12
Southwest	-0.31	-0.32	-0.37	-0.23	0.00	-0.06
West	-0.08	-0.36	-0.21	-0.14	0.04	-0.20
Northwest	0.14	-0.57	-0.04	-0.04	0.04	-0.31
North	0.07	-0.05	0.08	-0.14	0.00	0.03

Table 3. Differences to reference values taken from the results for the GP-ICPR method from (Bae, 2006).

Fig. 2 shows a coarse registration result for the Northeast and North positions. It can be observed that the North data (purple) is tilted a bit in one direction with respect to the other dataset. This is due to the tilted setup of the laser scanner that has not been accounted for by the registration algorithm. What can also be seen is the limited amount of overlapping areas between the positions which is typical for Agia Sanmarina data. There are hardly any purple planes pointing to other directions than North only. On the other hand, there are many green planes pointing North and East as this dataset had been taken from a corner of the church. However, matching object regions are close enough to each other so that a fine registration is possible.

4.4 Fine registration

The pairwise fine registration uses the initial transformation parameters output by the coarse registration and is carried out on the surface elements from which the large planes were composed. Even though a valid solution could be found rather easily, it turned out extremely difficult to find a set of thresholds that would work on all neighboring datasets.

Often, the plane based ICP gradually converged to a wrong solution. The reason is that the plane based adjustment step requires three independent planes to fix the translation. While this had not been a problem for other datasets tested previously, Agia Sanmarina data typically contains only one big facade. Often there is only little information on the orthogonal walls because the scanner had been positioned in front of the facade. The ground plane also is of bad quality since it is rough and does not display a suitable overlap.

An example for the fine registration is shown in Fig. 3. Matching parts now overlap quite well. Despite the difficulties with the convergence the fine registration also can be regarded as successful. As some manual intervention was needed for good choice of the thresholds, this step should be considered semi-automatic. However, it should be noted that only two out of the eight position pairs posed a problem and that the initial aim was to find a global set of thresholds.

Pairwise registration only leads to the propagation of errors. If the loop can be closed such as possible for Agia Sanmarina data, these errors become obvious. An example is shown in Fig. 4 (top). Especially at the top of the middle tower, the accumulated errors can be seen as a slight shift and rotation. Nevertheless, the overall quality of the fine registration seems to be quite well.

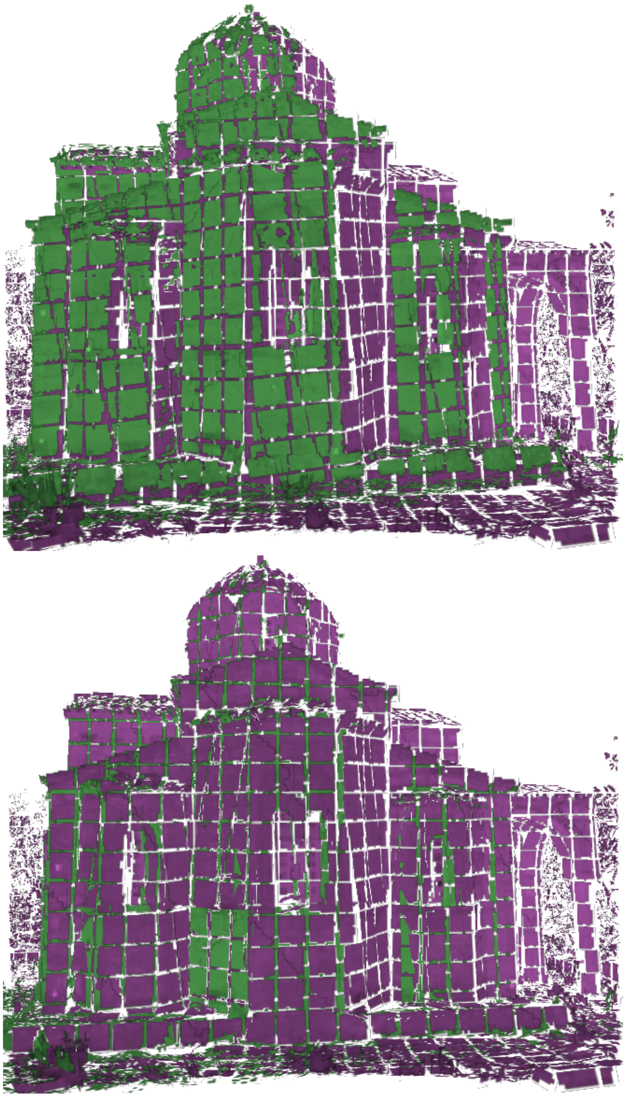

Figure 4. Top: Residual of the loop closing for consecutive fine registrations between Southeast (green) and East (purple) positions. Bottom: The same two positions after bundle adjustment.

4.5 Bundle adjustment

An improvement has been sought via a bundle adjustment of all datasets. The resulting transformation parameters are shown in Tab. 2. Similar to (Bae, 2006), an overall transformation had been carried out such that the East position has an identity transform as its parameters. As can be seen from Fig. 4 (bottom), the two positions are now registered with smaller residuals. There is a noticeable change in color because to a small remaining shift most of the surface elements from the East facade (purple) are slightly in front of those from the Southeast facade (green).

Tab. 3 shows the difference in the registration parameters obtained via the surface elements and those given in (Bae, 2006) that will be regarded as reference. Please note that the coordinate system used for our work is different from that of the reference data. Here, the z-axis is pointing upwards and the rotation angles are defined in a slightly different way. For comparison, the reference parameters had been transformed into our coordinate frame so that valid differences can be obtained.

(Bae, 2006) reports angular residuals that range from 0.0003° to 0.5°. Most of the time the residuals are less than 0.01° – we see that the plane based method is roughly ten times worse. For the translation the situation is similar as the reference has residuals in the order of about 1 cm whereas we found about 10 cm.

5 CONCLUSIONS

In this paper, an automatic registration method for terrestrial LIDAR data has been applied to the Agia Sanmarina test data supplied by ISPRS WG V/3. Three different steps have been tested, coarse registration, fine registration and a refined solution that uses all datasets simultaneously.

All steps were able to generate a solution on the test data. Especially the coarse registration can be considered as successful as it quite easily returned usable initial solutions. The pairwise fine registration, however, required quite a lot attention to the selection of proper thresholds so that a correct solution could be obtained for all neighboring pairs.

The bundle adjustment was able to improve the results from the fine registration, but could not achieve a satisfying result as the accuracy is about a factor of ten worse than the ICP-based reference solution. A probable cause could be the rather coarse surface elements that might be less accurate than their planar appearance suggests.

On the other hand, the data is not optimal for plane based approaches because the scene consists of one convex object covered with a lot of small structures. The approach should work better if more objects with larger planar surfaces are available.

We can conclude that registration based on surface elements is especially successful for coarse registration. Pairwise fine registration as well as a bundle adjustment style registration of an arbitrary number of datasets are possible as well, but the resulting accuracy is limited.

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