ACCURACY ASSESSMENT OF AIRBORNE LASER SCANNING STRIPS USING PLANAR FEATURES

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ABSTRACT:

Airborne Laser Scanning (ALS) is widely used in many applications for its high measurement accuracy, fast acquisition capability, and large spatial coverage. Accuracy assessment of the ALS data usually relies on comparing corresponding tie elements, often points or lines, in the overlapping strips. This paper proposes a new approach to strip adjustment and quality assessment of ALS data by using planar features. In the proposed approach a transformation is estimated between two overlapping strips by minimizing the distance between points in one strip and their corresponding plane in the other. The planes and the corresponding points are extracted in a segmentation process. The point-to-plane distances are used as observables in the estimation model, where the parameters of a transformation between two strips and their associated quality measures are estimated. We demonstrate the performance of the method on the AHN2 dataset over Zeeland province of The Netherlands. The dataset consists of 13 overlapping strips, from which a total of 522 gable roof and dike slope planes are extracted. The results show planimetric offsets between the strips that range from 3.13 cm to 55.32 cm. These offsets are in agreement with previously reported results using linear features. In addition, we estimated vertical offsets in the order of a few centimeters, which were not estimated in previous studies. The rotation parameters between the strips were also estimated; however, these did not show a significant difference in the orientation of the strips.

1. INTRODUCTION

Airborne Laser Scanning (ALS) is widely used in many applications for its high measurement accuracy, fast acquisition capability, and large spatial coverage. In the Netherlands, several LiDAR surveys are performed that cover the entire country. The second part of the national LiDAR elevation mapping AHN2 (Actueel Hoogtebestand Nederland) is being acquired since 2007 by several companies and will be completed in 2012. The elevation model is created from the LiDAR measurements that have an average density of 10 points per square meter. This unique high resolution LiDAR dataset is used in a variety of applications, e.g. water storage determination, subsidence studies, forest volume mapping, orthophoto creation and 3D modeling.

The ALS measurements are acquired in multiple flight strips, and are independently georeferenced using data from on-board navigation sensors, i.e. GPS and IMU. The systematic and random errors introduced by the scanning mechanism as well as the navigation sensors accumulate in the final point cloud. This results in an offset and misalignment between data of overlapping flight strips. The quantification and elimination of the offset and misalignment between the overlapping strips is an important issue in airborne laser scanning, and is commonly referred to as strip adjustment. Moreover, the identification of the offsets and misalignments forms a major part of the accuracy assessment done by the end-user of the data. Thus, both the data provider and the end-user of LiDAR data need a fast and reliable method to assess the quality of the strip adjustment.

In the past years, several strip adjustment methods have been developed. Existing approaches to strip adjustment are based on two main techniques. The first technique incorporates tie points that are common in two overlapping strips, and estimates an offset by minimizing the distance between the corresponding tie points (Burman, 2002; Filin and Vosselman, 2004; Kager, 2004; Morin and Ee-Sheimy, 2002; Paquet, 2003; Pfeifer et al., 2005). A major drawback of this method is that the identification of tie points in the point cloud is difficult due to the low point density. The second technique relies on the adjustment of corresponding lines in the overlap area of two strips (Habib et al., 2008; Maas, 2002; Rentsch and Krzystek, 2009; Vosselman, 2002; Vosselman, 2008). This method is an improvement of the adjustment of tie points, as linear features can be extracted more accurately. The lines can be extracted directly from the scan points, or can be derived as the intersection of two adjacent planes. In the latter case, the extracted lines are expected to be more accurate as more points contribute to the estimation of the line parameters.

This paper proposes a new approach to strip adjustment and quality control of airborne laser scanner data by using planar features. The basis of this approach is that without random and systematic errors, paired surface elements such as gable roofs and dike slopes in overlapping strips should perfectly match each other. The quality of the adjustment between these planar features in overlapping strips is used to detect systematic errors in the system parameters and to evaluate the noise level in the LiDAR data. In the proposed approach, a transformation is estimated between two overlapping strips by minimizing the distance between points in one strip and their corresponding plane in the other. The advantage of such an estimation model is twofold. First, by incorporating a large number of point-to-plane observations in a least-squares estimation model an improved accuracy of the estimated transformation parameters will be achieved. Second, by minimizing the point-to-plane distances not only can we obtain a 3D offset, but also the rotation parameters between the two strips. In addition, the estimation model is linear, which makes it independent of an initial estimate of the transformation parameters.

The paper is organized as follows. In Section 2 the first step of the proposed method is described, which concerns the segmentation and extraction of planar features. Section 3 presents the mathematical model for the estimation of the strip adjustment parameters. The results of the accuracy assessment of strip overlaps over Zeeland province are presented in Section 4. Conclusions are drawn in Section 5.

2. EXTRACTION OF PLANES FROM OVERLAPPING STRIPS

ALS data are normally acquired strip-wise, with across-track overlap, as shown in Figure 1. Data providers perform a strip adjustment procedure using data from onboard navigation sensors, i.e. GPS and IMU. In this paper, we consider the already adjusted point cloud supplied by the data provider. Errors in the laser measurements and inaccuracy in the strip adjustment procedure propagate in the final adjusted point cloud. To quantify the accuracy of the final point cloud, features in the overlap area of the strips are extracted and compared.

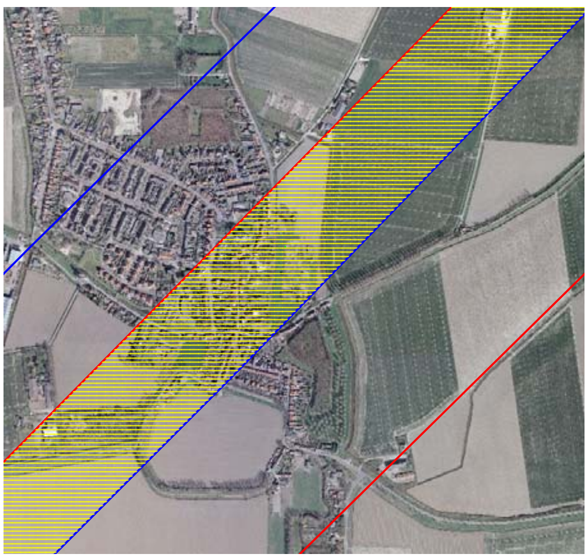


Figure 1: Overlapping strips. The overlap area between the blue strip and the red strip is represented as the yellow hatched area.

A point cloud consists of 3D Cartesian positions of surfaces that reflected emitted laser light. Point cloud data for each strip in the overlap area are interpolated into a raster format using an Inverse Distance Interpolation algorithm based on weighted average method (Weber and Englund, 1994) with a resolution of 50 centimeters. Slope and aspect orientation that define the best the terrain in the vicinity of each point data are derived. Homogenous regions are created by using a segmentation algorithm performed with the slope and aspect data. The segmentation algorithm is a bottom-up region-growing technique that starts with one-pixel seed regions. In the subsequent steps, smaller image regions are merged into larger ones forming objects with more pixels. The growing decision is based on local homogeneity criteria describing the similarity of the adjacent image objects in terms of size, distance, texture, spectral similarity and form (Baatz and Schape, 2000). User-defined thresholds are interactively set to enable the decision on the merger of the neighboring objects (Definiens, 2007).

Planar surfaces that represent gabled roofs and dike slopes are selected from the resulting segments by constraining the regions to a minimum area of 6 m^2 and a slope between 15 and 70 degrees. The boundaries of the corresponding regions in two strips are combined and the points that are within the intersection area are selected for the estimation of the plane parameters.

Plane parameters are obtained by applying a Principal Component Analysis (PCA) to the selected points. PCA provides the axis of minimum variation of elevation, which is an estimation of the normal vector of the plane. The distance of the plane to the origin of the coordinate system is taken as the median of the dot product of the normal vector and the vector of each individual point.

The points in one strip that are corresponding to the plane in the other strip might contain outliers, e.g. points on the walls or the ground surface. To deal with the outlying points a robust plane fitting can be applied to the points in both strips. Then only those points that are identified by the robust fitting algorithm as inliers are used to obtain the point-to-plane distances. The robust plane fitting is performed using the RANSAC algorithm. Considering that each random sample should contain a minimum of three points and assuming that 50% of the points are outliers, 35 random samples are needed to ensure with a probability of 99% that at least one sample is outlier-free (Fischler and Bolles, 1981). The relatively small number of required random samples indicates that the computational cost of the algorithm is easily affordable.

3. ESTIMATION OF STRIP ADJUSTMENT PARAMETERS

The output of the previous step is a set of planes in one strip and their corresponding points in the other strip. The parameters of a similarity transformation between the two overlapping strips are estimated by minimizing the distances between points and their corresponding planes. Let us express the condition that a set of points **P** transformed by a similarity transformation **H** lies on a plane $\boldsymbol{\pi}$ as (Hartley and Zisserman, 2003; Khoshelham and Gorte, 2009):

$$\boldsymbol{\pi}^{\mathrm{T}}\mathbf{H}\mathbf{P} = \mathbf{0} \tag{1}$$

where $\boldsymbol{\pi} = (n_1, n_2, n_3, -d)^{\mathrm{T}}$ represents a plane with normal $\mathbf{n} = (n_1, n_2, n_3)^{\mathrm{T}}$ and distance d to the origin, $\mathbf{P} = (x, y, z, 1)^{\mathrm{T}}$ denotes the homogenous representation of a point in 3D space, and **H** is a homogenous similarity transformation:

$$\mathbf{H} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}_{1\times 3} & 1 \end{bmatrix} \tag{2}$$

where **R** is a 3D rotation matrix and $\mathbf{t} = (t_x, t_y, t_z)^{\mathrm{T}}$ is a translation vector. A scale factor is ignored since the two overlapping laser strips are assumed to have identical scales. To estimate the rotation and translation that bring the points in one strip to lie on their corresponding plane in the other strip, we decompose Eq. (1) as follows:

$$\begin{bmatrix} n_1 & n_2 & n_3 & -d \end{bmatrix} \begin{bmatrix} \mathbf{r}_1^{\mathrm{T}} & t_x \\ \mathbf{r}_2^{\mathrm{T}} & t_y \\ \mathbf{r}_3^{\mathrm{T}} & t_z \\ \mathbf{0}_{1\times 3} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{p} \\ 1 \end{bmatrix} = 0 \tag{3}$$

where $\mathbf{r}_1^T$, $\mathbf{r}_2^T$, $\mathbf{r}_3^T$ are the three rows of the rotation matrix, and $\mathbf{p} = (x, y, z)^T$ is the Euclidian notation of a point in 3D space. For one point on one plane Eq. (3) reduces to:

$$n_1\left(\mathbf{r}_1^T\mathbf{p}+t_x\right)+n_2\left(\mathbf{r}_2^T\mathbf{p}+t_y\right)+n_3\left(\mathbf{r}_3^T\mathbf{p}+t_z\right)=d \tag{4}$$

Eq. (4) is the essential estimation model that basically expresses the condition that the rotated and translated points rest on their corresponding plane. For m points corresponding to k planes we will have a system of equations as follows:

$$\begin{bmatrix} n_1^1\mathbf{p}^{1\mathrm{T}} & n_2^1\mathbf{p}^{1\mathrm{T}} & n_3^1\mathbf{p}^{1\mathrm{T}} & n_1^1 & n_2^1 & n_3^1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ n_1^k\mathbf{p}^{m\mathrm{T}} & n_2^k\mathbf{p}^{m\mathrm{T}} & n_3^k\mathbf{p}^{m\mathrm{T}} & n_1^k & n_2^k & n_3^k \end{bmatrix} \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \mathbf{r}_3 \\ t_x \\ t_y \\ t_z \end{bmatrix} = \begin{bmatrix} d^1 \\ \vdots \\ d^k \end{bmatrix} \tag{5}$$

where superscripts denote the point and plane numbers. The system of equations (5) is of the form $\mathbf{AX} = \mathbf{L}$ for which the least-squares solution that minimizes the norm of the squared distances between the transformed points and their corresponding planes, i.e. $\|\mathbf{AX} - \mathbf{L}\|$, is given as Eq. (6):

$$\mathbf{X} = (\mathbf{A}^{\mathrm{T}}\mathbf{W}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{W}\mathbf{L} \tag{6}$$

where $\mathbf{W}$ is a weight matrix, which gives the same weight to each observable based on the assumption that all observables have the same precision.

A special case of the strip adjustment model as described above occurs when the rotation parameters are not of interest or can be ignored. In this case, the transformation matrix will consist only of translation parameters, and the estimation model given in Eq. (6) reduces to:

$$n_1\left(x+t_x\right)+n_2\left(y+t_y\right)+n_3\left(z+t_z\right)=d \tag{7}$$

which basically expresses that the translated points lie on the plane. The system of equations with m points and k planes becomes:

$$\begin{bmatrix} n_1^1 & n_2^1 & n_3^1 \\ \vdots & \vdots & \vdots \\ n_1^k & n_2^k & n_3^k \end{bmatrix} \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} = \begin{bmatrix} d^1 - n_1^1x^1 - n_2^1y^1 - n_3^1z^1 \\ \vdots \\ d^k - n_1^kx^m - n_2^ky^m - n_3^kz^m \end{bmatrix} \tag{8}$$

for which a solution that minimizes the distances between the translated points and their corresponding planes can be obtained similar to the general case as given in Eq.(4).

It is worth noting that to obtain a solution for the estimation models derived above the design matrices in Eqs. (5) and (8) have to be of full rank. This requires a minimum of 9 points and 3 non-parallel planes to estimate the similarity transformation in Eq. (5), and a minimum of 3 points and 3 non-parallel planes to estimate the translation vector in Eq. (8).

The precision of the observables as well as the estimated transformation parameters are derived from the residual vector $\mathbf{v}$ that actually contains the remaining point-to-plane distances after the adjustment:

$$\mathbf{v} = \mathbf{AX} - \mathbf{L} \tag{9}$$

The reference variance obtained from the residual vector $\mathbf{v}$ is an indication of the precision of the observables:

$$\sigma_0^2 = \frac{\mathbf{v}^{\mathrm{T}}\mathbf{W}\mathbf{v}}{n-m} \tag{10}$$

The precision of the estimated transformation parameters is obtained by Eq. (11):

$$\mathbf{\Sigma}_{\mathbf{xx}} = \sigma_0^2(\mathbf{A}^{\mathrm{T}}\mathbf{W}\mathbf{A})^{-1} \tag{11}$$

4. EXPERIMENTAL RESULTS

4.1 Description of dataset

To experiment with the point-to-plane strip adjustment method we use the pilot AHN2 dataset acquired by Fugro-Inpark over Zeeland province in 2007. The area consists of a crop land with large farm buildings and several urban areas, of which the city of Flushing is the largest. The data were acquired with the FLI-MAP 400 system mounted on a helicopter (Fugro, 2007). Two on-board GPS receivers were combined with five reference stations on the ground. The data was acquired at a flight height of 375 meters. Data of this survey were delivered in three files per strip, in ascii xyz format, corresponding to the forward-, nadir- and backward- looking scan lines. These files were combined and converted to LAS format for more efficient processing.

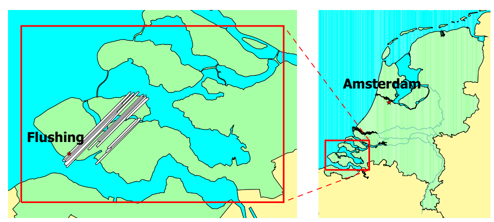


Figure 2: Zeeland (The Netherlands) AHN2 dataset coverage, consisting of 15 overlapping flight strips.

From this dataset 15 flight strips were selected, resulting in 13 strip overlaps, as shown in Figure 2. The 15 chosen strips with their corresponding number of points are listed in Table 1. Each of the strips has a width of approximately 460 meters and an overlap of 100 meters.

Table 2 lists the overlaps and their corresponding strips, number of points and width of each overlap. The overlaps are of different sizes and contain various numbers of points. Within each overlap also the numbers of points belonging to each strip are slightly different, which is due to the difference in the scanning geometry, the topography and the type of objects present in the overlap area.

Table 1: List of the 15 selected flight strips with their number of measured scan points.

Flight Strip #	Flight Strip ID	Number of points
s1	070308_121845	109,340,275
s2	070308_123815	4,618,326
s3	070308_124330	132,846,682
s4	070308_155104	121,702,750
s5	070308_163230	105,330,801
s6	070308_165626	121,535,336
s7	070314_082253	112,672,554
s8	070314_084049	88,736,678
s9	070314_085255	88,918,902
s10	070314_102526	90,397,311
s11	070317_105333	39,763,835
s12	070319_144341	78,477,077
s13	070319_145835	60,590,540
s14	070319_150744	8,279,387
s15	070319_151007	61,851,723

Table 2: List of the 13 overlap areas with the number of points considered per overlap area and the overlap area width.

Overlap #	Flight Strip		Number of points in Strip		Overlap Width (m)
	1	2	1	2	
o1	s3	s4	21,731,922	27,885,585	200
o2	s4	s5	23,114,236	28,984,667	175
o3	s5	s6	28,984,667	51,271,482	240
o4	s7	s8	24,693,624	24,953,061	175
o5	s9	s8	24,534,357	22,834,121	175
o6	s9	s10	35,156,934	22,427,804	240
o7	s10	s11	10,303,345	7,590,510	200
o8	s12	s13	24,771,459	19,671,036	240
o9	s14	s13	3,267,309	4,177,717	525
o10	s15	s13	22,910,115	14,855,334	240
o11	s2	s1	4,618,326	5,251,392	485
o12	s2	s3	4,618,326	6,164,108	485
o13	s1	s3	65,247,718	77,060,363	320

4.2 Results

Each overlap area was segmented and the planar regions were extracted as described in Section 2. Each extracted region contained a number of points from the first strip and a number of points from the second strip. Table 2 lists the total number of points that were extracted in the segmentation procedure. For each region, point-to-plane distances were derived as follows: to the points from the second strip a plane was fitted using the PCA method. The distances between this plane and the points in the corresponding region in the first strip were used as observables in the adjustment model.

To assess the quality of the strips, offset and misalignment between the overlapping strips are estimated. In addition, the mean and standard deviation of the point-to-plane distances before and after the adjustment are evaluated. Assuming that the data are not contaminated by gross errors (outliers), the mean before the adjustment indicates the offset between the strips if the standard deviation is small. After the adjustment, the mean is expected to be very small, while the standard deviation indicates the precision of the observables and also the estimated parameters.

Before the adjustment, the mean of the point-to-plane distances ranges from -7 cm to 9 cm across the overlaps, while the standard deviation is between 14 cm and 52 cm. The strip adjustment model with translation parameters only was first applied assuming that there is only an offset between the overlapping strips. After the adjustment the mean of the point-to-plane distances was found to range from -3 cm to 7 cm across the overlaps, and the standard deviation remained more or less the same for all overlaps.

The relatively large mean and standard deviation of the point-to-plane distances after the adjustment might have two possible reasons: i) the transformation between the two strips should contain both rotation and translation parameters (misalignment between the strips); ii) the planar regions contain outlying points, which influence the least-squares estimation of the transformation parameters.

To verify the presence of misalignment between the overlapping strips the adjustment model with the full similarity transformation was applied. The resulting mean of point-to-plane distances ranged from -1 cm to 2 cm across the overlaps; however, the standard deviation still remained large for most overlaps, with a maximum of 40 cm for overlap o3.

To investigate the influence of outliers in the estimation model, the planes were recomputed using RANSAC as described in Section 2. This also provided a set of outlying points that were withdrawn from the estimation model. The results of both adjustment models with inlying point-to-plane distances showed significant improvements over the previous results.

Figure 3 shows the mean of the point-to-plane distances before and after the adjustment with and without RANSAC for outlier detection. It clearly shows that removing outliers improves the mean, both before and after the adjustment. Before the adjustment, with outliers detected and removed, the mean is within -4 cm and 4 cm. By using the translation model for the adjustment, the mean reduces for all the overlaps, except for overlap o2 (although here the mean is only 1 cm). Using a full similarity transformation further reduces the mean, which implies the presence of misalignment between the strips.

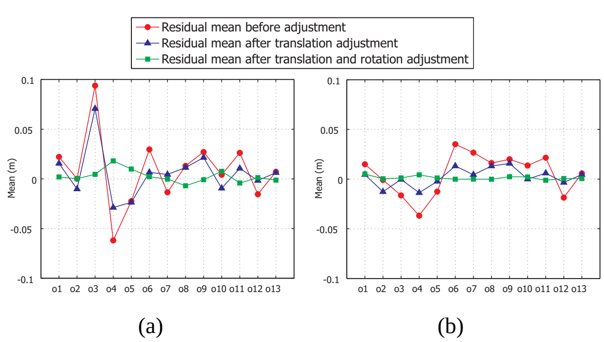
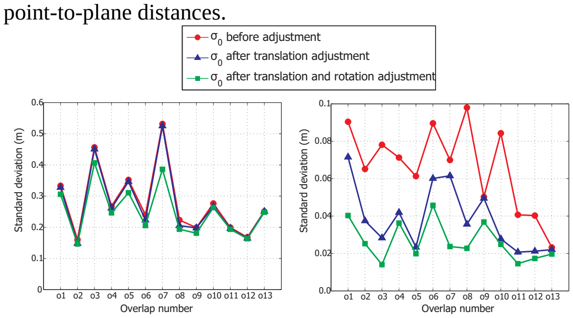


Figure 3: Mean of the point-to-plane distances for 13 overlaps (a) without RANSAC outlier detection, (b) with RANSAC outlier detection.

Figure 4 shows the standard deviation of the point-to-plane distances before and after the adjustment, with and without RANSAC outlier detection. Removing the outliers results in an improvement of the standard deviation by a factor 5. The standard deviations are smaller after the adjustment, and are the smallest when a full similarity transformation is used in the adjustment model. Considering that the similarity transformation results in very small means, the corresponding standard deviations are indications for the precision of the point-to-plane distances.



(a) (b)

Figure 4: Standard deviation of the point-to-plane distances for 13 overlaps (a) without RANSAC outlier detection, (b) with RANSAC outlier detection.

The estimated transformation parameters, together with their estimated precisions, were compared to the results of a previous method that uses line segments as tie elements for the adjustment (Vosselman, 2002). This method provides only 2D translation parameters, T_x and T_y. Figure 5 shows a comparison of the estimated 2D translation parameters and their associated precisions. The precision of the estimated parameters is better in all overlaps when point-to-plane distances are used. Except for T_x obtained by the similarity adjustment model in overlap o7, the overall precision of the offsets estimated by the point-to-plane distances is better than 1 mm. In most of the overlaps, T_x and T_y estimated by both methods are in agreement, except for T_x in overlaps o7 and o9, where differences of about 2 cm can be observed. For overlap o9, the precision of T_x estimated from line correspondences is very low whereas T_x estimated with the point-to-plane distances using both adjustment models are more precise and in fact identical. The disagreement in T_x corresponding to overlap o7 may be due to the presence of larger misalignment between the strips.

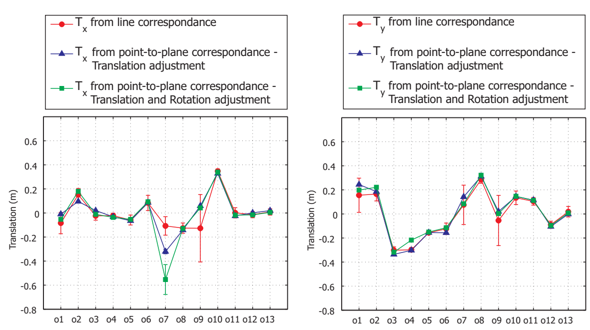


Figure 5: Comparison of 2D translation parameters estimated from line correspondences and point-to-plane distances.

Figure 6 shows the comparison of the vertical offset T_z estimated by the two transformation models. It can be seen that both methods result in the same vertical offsets, with very small differences (~1 cm) in overlap o3 and o7. The precision of the estimated vertical offsets is better than 1 mm.

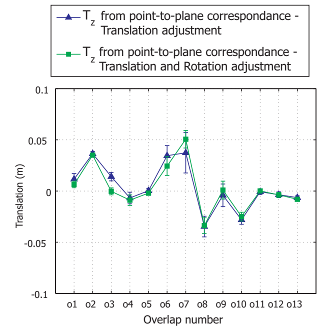


Figure 6: Comparison of vertical offset T_z estimated by the two adjustment models. The standard deviation bars are scaled up by a factor of 10.

In general, when point-to-plane distances are used, the estimated offsets are the same for both adjustment models, the translation only and the full similarity. In fact, the rotation parameters were found to be very small. However, the precision of the estimated offsets is better when full similarity model is used. The estimated offsets between the strips in x- and y-direction are in general larger than the vertical offsets, and vary between 0 and 40 cm across the overlaps. The largest vertical offset is only 5 cm.

5. CONCLUSIONS

We have presented a method for quality control and adjustment of airborne laser strips based on planar features. The distances between points in one strip and their corresponding planes in the overlapping strip are used as observables in a linear least-squares model to estimate offsets and misalignment between the overlapping strips. The performance of the method was demonstrated using the AHN2 laser dataset consisting of 15 flight strips. The offsets between the overlapping strips were found to range between 0 and 40 cm for the horizontal offsets, and smaller than 5 cm for the vertical ones. The misalignments between the strips were very small. Outlier detection was shown to play an important role in obtaining reliable and precise transformation parameters. Using RANSAC for robust plane fitting and outlier detection led to a better precision for the estimated parameters as compared to previous methods. Moreover, the estimation of both translation and rotation parameters provided better adjustment of the strips, and therefore more thorough quality assessment. From a computational perspective, the method is very efficient thanks to the linear estimation model.

Currently our segmentation is carried out interactively. Future research will focus on developing a reliable automatic segmentation method to speed up the quality assessment process. In addition, we plan to compare the performance of this method with other existing strip adjustment methods.

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