LIDAR STRIP ADJUSTMENT USING CONJUGATE LINEAR FEATURES IN OVERLAPPING STRIPS

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ABSTRACT:

LiDAR (Light Detection And Ranging) is a multisensory system consisting of three main components: laser, GPS, and IMU units. The basic principle is to measure distances from the sensor to the ground by converting the travel time information of the laser pulses sent to the earth. A scanning mechanism, usually a scanning mirror, is used to collect the data in a strip-wise fashion. The ground coordinates of the laser footprints are derived using the direct geo-referencing information furnished by the onboard GPS/IMU unit and the calibration parameters determined through a calibration procedure. When the calibration parameters are not accurately determined, systematic discrepancies between overlapping strips might occur. The ideal solution for the adjustment of neighboring strips is the implementation of an accurate calibration procedure. However, such a calibration demands the original observations (GPS, IMU and the laser measurements), which are not usually available to the end-user. In this work, a strip adjustment procedure for reducing or eliminating discrepancies between overlapping LiDAR strips is proposed. The mathematical model employed is similar to that used in the photogrammetric Block Adjustment of Independent Models (BAIM). Generally, a traditional BAIM uses conjugate points. These features, however, are not suitable for LiDAR surfaces since it is almost impossible to identify conjugate points in overlapping LiDAR strips. In this work, the use of linear features, which are represented by sets of non-conjugate points, is investigated. The non-correspondence of the selected points along the linear features is compensated for by artificially expanding their variance-covariance matrices. The paper presents experimental results from real data illustrating the feasibility of the proposed procedure.

1. INTRODUCTION

A LiDAR system is basically composed of a laser ranging and scanning unit and a position and orientation system (POS), which consists of an integrated differential global positioning system (DGPS) and an inertial measurement unit (IMU). The principle of laser ranging is to measure distances from the sensor to the ground. The GPS system provides position information and the IMU provides attitude information. The coordinates of the LiDAR footprints are the result of combining the derived measurements from each of its system components, as well as the bore-sighting parameters relating such components. The relationship between the system measurements and parameters is embodied in the LiDAR equation (Vaughn et al., 1996; Schenk, 2001; El-Sheimy et al., 2005), Equation 1. As it can be seen in Figure 1, the position of the laser footprint, $\vec{X}_G$, can be derived through the summation of three vectors ($\vec{X}_o$, $\vec{P}_G$ and $\vec{\rho}$) after applying the appropriate rotations: $R_{yaw,\ pitch,\ roll}$, $R_{\Delta\omega,\Delta\phi,\Delta\kappa}$ and $R_{\alpha,\beta}$. In this equation, $\vec{X}_o$ is the vector from the origin of the ground coordinate system to the origin of the IMU coordinate system, $\vec{P}_G$ is the offset between the laser unit and IMU coordinate systems (bore-sighting offset), and $\vec{\rho}$ is the laser range vector whose magnitude is equivalent to the distance from the laser firing

point to its footprint. The term $R_{yaw,\ pitch,\ roll}$ stands for the rotation matrix relating the ground and IMU coordinate systems, $R_{\Delta\omega,\Delta\phi,\Delta\kappa}$ represents the rotation matrix relating the IMU and laser unit coordinate systems (angular bore-sighting), and $R_{\alpha,\ \beta}$ refers to the rotation matrix relating the laser unit and laser beam coordinate systems with α and β being the mirror scan angles. For a linear scanner, which is the focus of this paper, the mirror is rotated in one direction only leading to zero α angle. The involved quantities in the LiDAR equation are all measured during the acquisition process except for the bore-sighting angular and offset parameters (mounting parameters), which are usually determined through a calibration procedure.

Due to systematic errors in the LiDAR components and/or resulting from their integration, adjacent LiDAR strips might exhibit discrepancies. Such systematic discrepancies are caused by missing or improperly employed calibration and operational procedures. The ideal solution for obtaining a homogeneous dataset, with overlapping strips coinciding properly is the implementation of an accurate calibration procedure. However, a calibration procedure demands the original observations (GPS and IMU measurements and laser scanner observations), which are not usually available to the end user. Instead, only the XYZ-coordinates of the LiDAR
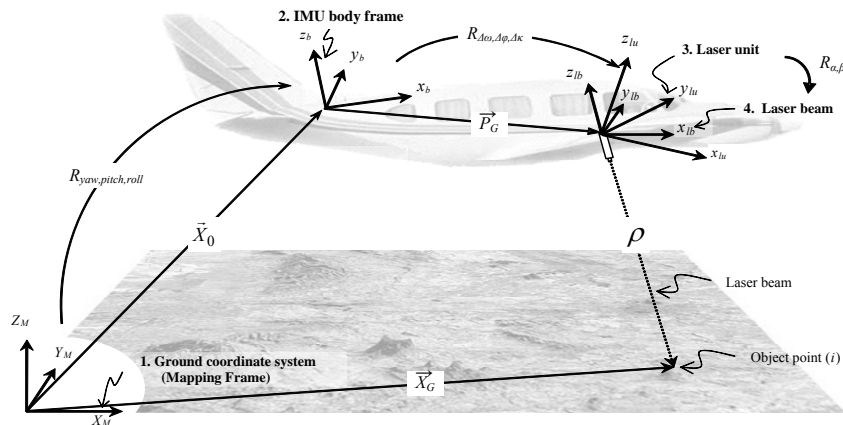
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Figure 1. Coordinate systems and involved quantities in the LiDAR equation

$$\vec{X}_G = \vec{X}_o + R_{yaw,\ pitch,\ roll}\ \vec{P}_G + R_{yaw,\ pitch,\ roll}\ R_{\Delta\omega,\ \Delta\phi,\ \Delta\kappa}\ R_{\alpha,\ \beta} \begin{bmatrix} 0 \\ 0 \\ -\rho \end{bmatrix} \quad (1)$$

footprints are provided. Therefore, methods for adjusting LiDAR strips, which are only based on the XYZ-coordinates, are required.

In the past few years, several methods have been developed for evaluating and/or improving LiDAR data quality by checking the compatibility of LiDAR footprints in overlapping strips (Kilian et al., 1996; Crombaghs et al., 2000; Maas, 2000; Bretar et al., 2004; Vosselman, 2004; Pfeifer et al., 2005). In Crombaghs et al. (2000), a method for reducing vertical discrepancies between overlapping strips is proposed. This approach does not deal with planimetric discrepancies, which might have larger magnitude when compared with vertical discrepancies. In Kilian et al. (1996), an adjustment procedure similar to the photogrammetric strip adjustment was introduced for detecting discrepancies and improving the compatibility between overlapping strips. The drawback of this approach is relying on distinct points to relate overlapping LiDAR strips and control surfaces. Due to the irregular nature of the LiDAR footprints, the identification of distinct points (e.g., building corners) is quite difficult and not reliable. More suitable primitives have been suggested by Maas (2000), where the correspondence is established between discrete points in one LiDAR strip and TIN patches in the other one. The correspondences are derived through a least-squares matching procedure where normal distances between conjugate point-patch pairs are minimized. This work focused on matching conjugate surface elements rather than improving the compatibility between neighbouring strips. Bretar et al., (2004) proposed an alternative methodology for improving the quality of LiDAR data using derived surfaces from photogrammetric procedures. The main disadvantage, which limits the practicality of this methodology, is relying on having aerial imagery over the same area. In Pfeifer et al. (2005) and Vosselman (2004), other methods were developed for detecting discrepancies between overlapping strips.

The main objective of this paper is to present a new procedure for the strip adjustment while utilizing appropriate primitives that can be extracted from the LiDAR data with a satisfactory level of automation (i.e., requiring minimum user interaction).

The paper starts with a brief discussion of the LiDAR error budget. Then, the proposed procedure for the strip adjustment, including the extraction and matching of the appropriate primitives, is presented. The performance of the proposed strip adjustment procedure is evaluated through experimental results from real data. Finally, the paper presents some conclusions and recommendations for future work.

2. LiDAR ERROR BUDGET

The quality of the derived point cloud from a LiDAR system depends on the random and systematic errors in the system measurements and parameters. A detailed description of LiDAR random and systematic errors can be found in Huising and Pereira (1998), Baltsavias (1999), and Schenk (2001). The magnitude of the random errors depends on the accuracy of the system's measurements, which include position and orientation measurements from the GPS/IMU, mirror angles, and ranges. Systematic errors, on the other hand, are mainly caused by biases in the bore-sighting parameters relating the system components as well as biases in the system measurements (e.g., ranges and mirror angles). As a strip adjustment procedure is concerned with minimizing the impact of systematic errors in the LiDAR system on the derived point cloud, it is mandatory to understand the nature and impact of possible systematic errors in a LiDAR system.

In this work, a simulation process was carried out to analyse the impact of systematic errors/biases in the bore-sighting parameters (spatial and rotational) on the derived point cloud. The process starts from a given simulated surface and trajectory, which are then used to derive the system measurements (ranges, mirror angles, position and orientation information for each pulse). Then, biases are added to the system parameters, which are used to reconstruct the surface through the LiDAR equation. The differences between the bias-contaminated and true coordinates of the footprints within the mapped area are used to represent the impact of a given bias in the system parameters or measurements. Due to the presence of systematic errors in the system parameters, the bias-contaminated coordinates of

conjugate points in overlapping strips will show systematic discrepancies. The following conclusion could be drawn from the simulation experiments:

(1) The discrepancies caused by the bore-sighting offset and angular biases can be modelled by shifts and a rotation across the flight direction. Therefore, a six-parameter rigid-body transformation (three shifts and three rotations) is sufficient for modelling the introduced discrepancies and for aligning overlapping strips.

(2) A rigid-body transformation, on the other hand, cannot be used to align the strips relative to the ground coordinate system.

(3) In the presence of systematic errors in the bore-sighting parameters, averaging the spatial coordinates in overlapping strips will lead to a surface which is closer to the ground truth (the effects of the systematic errors are cancelled out or minimised).

3. STRIP ADJUSTMENT

The main goal of strip adjustment is to minimize the impact of systematic errors in the LiDAR system parameters by improving the compatibility among neighbouring strips. In addition, the estimated transformation parameters relating overlapping strips can be used to verify the quality of the system calibration. In the absence of biases in the system parameters, overlapping strips should coincide with each other without the need for any shifts or rotations. In other words, significant deviations from zero shifts and rotations can be used as an indication of the presence of systematic errors in the data acquisition system. Improving the compatibility between neighbouring strips can be viewed as the co-alignment of the different strips to a common reference frame. Therefore, the strip adjustment can be thought of as a registration procedure. An effective registration process should deal with four main issues: the registration primitives, establishing the correspondence between conjugate primitives, the transformation function relating the reference frames of the involved datasets, and the similarity measure which utilizes conjugate primitives for the estimation of the involved parameters in the transformation function. As it has been mentioned in the previous section, a six-parameter rigid-body transformation can be used as the transformation function relating overlapping strips in the presence of biases in the bore-sighting parameters. Traditional registration procedures (e.g., photogrammetric Block Adjustment of Independent Models – BAIM) are usually based on point primitives. These primitives, however, are not suitable when dealing with LiDAR data since it is quite difficult to establish the correspondence between distinct points in the irregularly-distributed footprints. Therefore, the use of linear features is proposed in this work. In the following sub-sections, the extraction and matching of primitives will be described. Also, the similarity measure, which incorporates the extracted primitives for the estimation of the parameters of the transformation function, will be presented.

3.1 Primitives Extraction and Matching

Since the LiDAR footprints are irregularly distributed, no point-to-point correspondence can be assumed between overlapping strips. In this regard, other primitives must be investigated. In this work, the use of linear features derived from the intersection of neighbouring planar patches is proposed. LiDAR provides high redundancy in planar surfaces. Therefore, the

plane parameters can be derived with high accuracy using an adjustment procedure (e.g. plane fitting). The larger the planar surface, the greater will be the point cloud noise reduction. Therefore, high accuracy linear features can be extracted by intersecting neighbouring planes. To do so, an environment for the extraction and matching of linear features in overlapping strips was developed. The process starts by displaying the LiDAR intensity images for overlapping strips where the operator selects an area where linear features might exist (e.g. roof ridge line). The user clicks on the centre of the area after defining the radius of a circle, within which the original LiDAR footprints will be extracted. It should be noted that the LiDAR intensity images are only used for visualization purposes. The user needs to establish the area of interest in one of the strips and the corresponding areas in the other strips are automatically defined. Figure 2a shows the specified area in one of the strips as well as the original LiDAR footprints in that area. Then a segmentation technique (Kim et al., 2007) is used to identify planar patches in the point cloud within the selected area. This segmentation procedure is independently run on the point cloud for all the overlapping strips. The outcome from such segmentation is aggregated sets of points representing planar patches in the selected area (bottom right portion in Figure 2b). For the linear features extraction, neighbouring planar patches are identified and the plane parameters determined. Then the neighbouring planes are intersected to produce an infinite straight-line. Then, using the segmented patches, the infinite line and a given buffer, the end points for the intersected line can be defined (top left portion in Figure 2b). This procedure is repeated for several areas within the overlap portion in the involved strips.

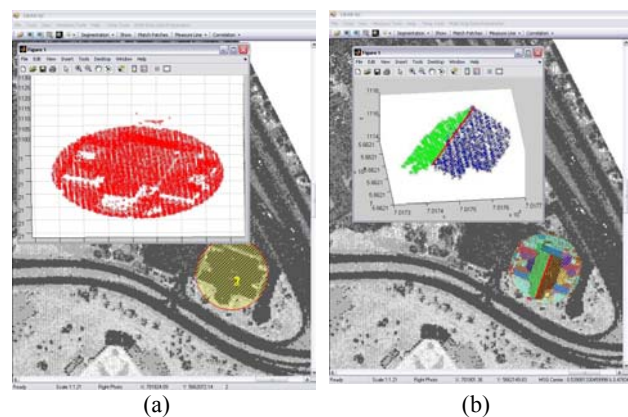(a)   (b)

Figure 2. Area of interest selection and LiDAR point cloud extraction (a), and extracted linear features by intersection of segmented planar patches in the area of interest (b)

The outcome of the extraction procedure is a set of linear features in overlapping strips. Due to the nature of the LiDAR data acquisition (e.g., scan angle, surface normal, surface reflectivity, occlusions), there is no guarantee that there is one-to-one correspondence between the extracted primitives from overlapping strips. To solve the correspondence problem, one has to utilize the attributes of the extracted lines. Conjugate lines can be automatically matched using the normal distance, parallelism, and the percentage of overlap between candidate lines in overlapping strips (Figure 3). A graphic visualization of matched linear features is presented to the user for final confirmation of the validity of the matched primitives.
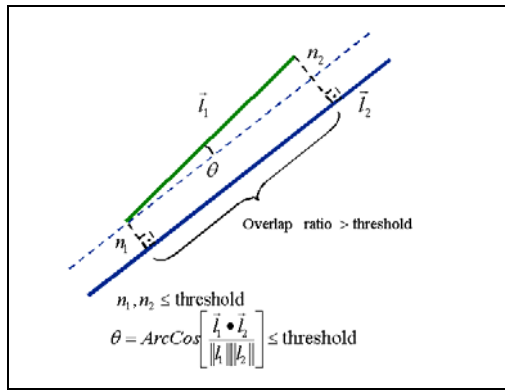
Figure 3. Matching of conjugate linear features in overlapping strips

3.2 Similarity Measure

So far, a semi-automated approach for the extraction of linear features from overlapping strips was presented. The extracted primitives are then matched using their respective attributes. In this section, the similarity measure, which incorporates the matched primitives together with the established transformation function to mathematically describe their correspondence, is introduced. The formulation of the similarity measure depends on the representation scheme for the involved primitives. In this work, a linear feature will be represented by its end points. It should be noted that the points representing corresponding linear features are not necessarily conjugate to each other. In this research, a point-based similarity measure, which can deal with non-conjugate points, is proposed. More specifically, a rigid body transformation (Equation 2) will be used to relate the observed strip coordinates (X_S, Y_S, Z_S) to the adjusted strip coordinates ($X_{S_A}, Y_{S_A}, Z_{S_A}$). Such a transformation will minimize the inconsistency among overlapping strips. The adjusted strip coordinates together with the parameters of the transformation function for the involved strips will be estimated through a Least Squares Adjustment (LSA) procedure.

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + R_{\omega,\phi,\kappa} \begin{bmatrix} X_{S_A} \\ Y_{S_A} \\ Z_{S_A} \end{bmatrix} \quad (2)$$

In order to compensate for the fact that the observed points along corresponding lines in overlapping strips are not conjugate, one can manipulate the variance-covariance matrices $\sum_{XYZ}$ (Equation 3) for such points. First, a local orthogonal coordinate system *UVW* is defined with the *U* axis aligned along the line direction (Figure 4). The rotation matrix *R*, which is used to establish the relationship between the *UVW* coordinate system and the *XYZ* coordinate system (Equation 4), is defined by the line direction. Then, using the law of error propagation, the variances of the line end points in the local coordinate system are derived from the variance-covariance matrix in the data coordinate system (Equation 5). A large number N is added to the variance along the line direction *U* (Equation 6). Finally, the variance-covariance matrix $\sum'_{XYZ}$ in the original coordinate system can be derived according to Equation 7.
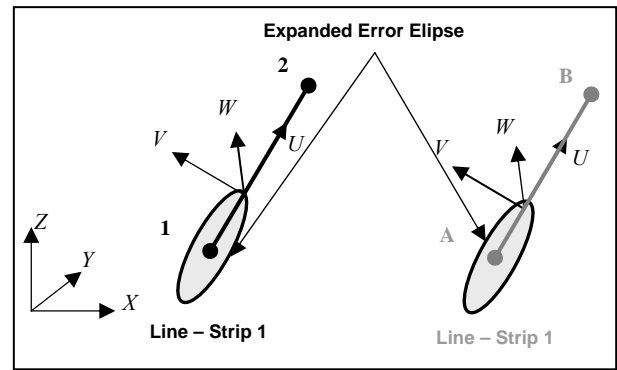

Figure 4. Variance-covariance expansion along the line direction

$$\sum_{XYZ} = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{YX} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{ZX} & \sigma_{ZY} & \sigma_Z^2 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = R \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (4)$$

$$\sum_{UVW} = R \sum_{XYZ} R^T \quad (5)$$

$$\sum'_{UVW} = \sum_{UVW} + \begin{bmatrix} N & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (6)$$

$$\sum'_{XYZ} = R^T \sum'_{UVW} R \quad (7)$$

In summary, the proposed strip adjustment procedure proceeds as follows:

(1) Using the developed interface, the user defines the areas of interest in the intensity images of some strips. The areas of interest are then automatically identified in all other strips where the linear features are extracted and matched. The corresponding linear features are represented by their end points, which might not be conjugate. The points representing corresponding linear features, however, will be assigned the same identification code.

(2) For each of the points representing the extracted linear features, one can write the observation equations similar to those in equation (2). Six transformation parameters (three shifts and three rotations) are used for each of the involved strips. To compensate for the fact that the utilized points along corresponding lines are not conjugate, their variances should be expanded along the line direction. The modified variances of the points in the local coordinate systems associated with the linear features are calculated according to equation (6). The modified variances in the strip coordinate system are then derived using equation (7). The variance expansion should be carried out for all the points sharing the same identification code except one. The point without variance expansion will be used to define the adjusted coordinates of that point along the linear feature in question. Maintaining the variance for that point is necessary since the variance-expansion process only

controls the point position in the normal direction to the enclosing feature.

(3) The transformation parameters for the individual strips as well as the adjusted strip coordinates of the observed features are determined through a LSA procedure. During such an adjustment procedure, the individual strips are independently rotated and shifted until they fit together as well as possible. The datum for the strip adjustment procedure can be established by using one of the strips as a reference strip. In other words, overlapping strips will be rotated and shifted until they are compatible with each other and fit with the reference strip as well as possible.

(4) The estimated transformation parameters in the previous step are applied to the respective strips leading to improved compatibility among these strips.

4. EXPERIMENTAL RESULTS

The experimental results section aims at testing the validity of the presented procedure using a real dataset as well as exploring the impact of such an adjustment procedure. It will start by describing the dataset used followed by the strip adjustment results.

4.1 Dataset Description

The dataset used in the experiments covers and urban area and consists of three strips as shown in Figure 5. The specifications of this dataset are shown in Table 1.
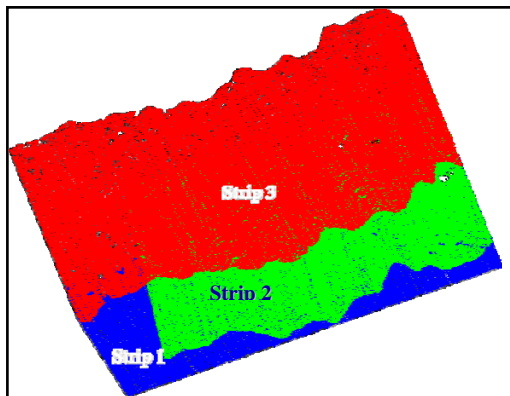

Figure 5. Dataset used in the experiments

Sensor Model	Optech 2050
Flying Height	~1000 m
Ground Point Spacing	~0.75 m
1 survey day	3 strips
Horizontal accuracy	50 cm
Vertical accuracy	15 cm

Table 1. Dataset specifications

4.2 Strip Adjustment Results

The proposed semi-automated procedure for the extraction and matching of corresponding linear features has been applied leading to the identification of twenty-eight lines in the three strips. These features are identified in the strips they appear (Figure 6). The points representing these features, after the variance expansion, are then used in a LSA procedure to estimate the transformation parameters for the involved strips as well as the adjusted strip coordinates. The estimated transformation parameters are listed in Table 2. A closer look at this table reveals the following:

1. Significant differences from the expected zero shifts and rotations indicate the presence of biases in the system bore-sighting parameters.
2. The most significant deviation is observed in the X-direction (refer to the X_T values in Table 2).
3. The least deviation from the optimum values is observed in the Z-direction (refer to the Z_T values in Table 2).

Strip	Lines Measured	X_T (m)	Y_T (m)	Z_T (m)	ω (°)	φ (°)	κ (°)
1	20	0.39	0.07	-0.02	-0.017	-0.008	0.003
2 *	26	0	0	0	0	0	0
3	17	0.66	-0.18	0.11	-0.037	-0.012	-0.009

*Reference strip

Table 2. Estimated transformation parameters using conjugate linear features in overlapping strips
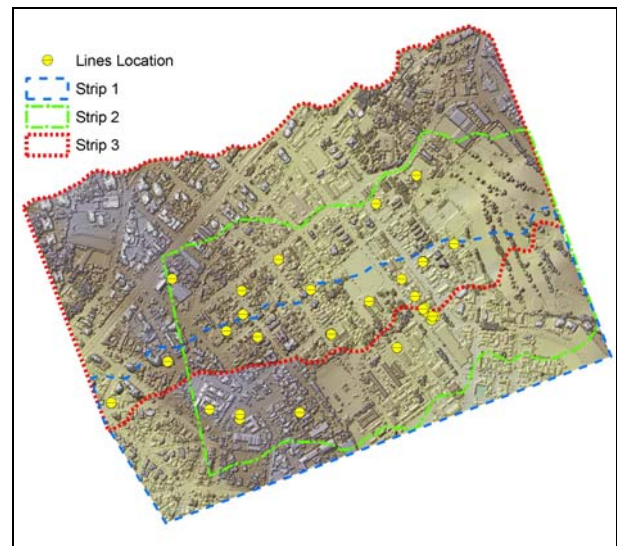

Figure 6. Location of the linear features used in the strip adjustment

The improvement in the strips' compatibility after the strip adjustment procedure can be observed in the profile shown in Figure 7. The surface shown in this profile is tilted with the aspect almost parallel to the X-axis, which is the direction where the most significant discrepancy takes place (refer to the X_T values in Table 2).
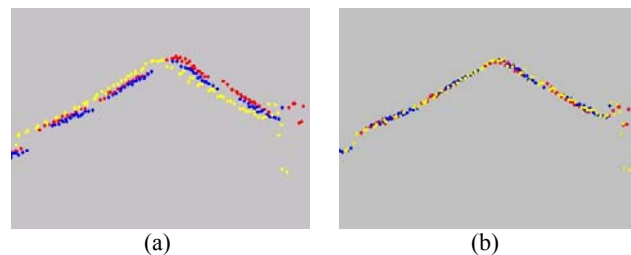

(a)   (b)

Figure 7. Profile along the X-axis crossing a tilted surface before (a) and after (b) the strip adjustment

One should note that the presented strip adjustment procedure mainly aims at improving the alignment between the strips and this does not necessarily mean improving the alignment of the adjusted strips relative to the ground coordinate system. In other words, one of the strips is chosen to be as a reference strip and the remaining strips are aligned relative to that strip, which is not bias free.

5. CONCLUSIONS

The direct acquisition of a high density and accurate 3D point cloud has made LiDAR systems the preferred technology for the generation of topographic data to satisfy the needs of several applications (e.g., digital surface model creation, digital terrain model generation, orthophoto production, 3D city modeling, and forest mapping). The non-transparent and sometimes empirical calibration procedures, however, might lead to consistent discrepancies between conjugate surface elements in overlapping strips. This paper presented a procedure to improve the compatibility among overlapping strips. First, the impact of systematic errors in the bore-sighting parameters on the derived point cloud was investigated. Then, a semi-automated approach for the extraction and matching of conjugate linear features in overlapping strips was introduced. The extracted linear features are represented by a set of non-conjugate points. The established transformation function and the matched primitives were used to estimate the necessary transformation parameters for the best co-alignment of the LiDAR strips. The non-correspondence of the selected points along the linear features is compensated for by artificially expanding their variance-covariance matrices along the line direction. Other than the co-alignment of overlapping strips, the developed procedure can be used to infer the presence of systematic errors in the data acquisition system. For an accurately calibrated LiDAR system, no shifts and rotations are needed to improve the compatibility of overlapping strips. Deviations from zero shifts and rotation can be used for the quality control the LiDAR system and derived data.

The performance of the proposed procedure was evaluated using real dataset. The experimental results revealed that the strip adjustment would improve the strips' compatibility and as a consequence the further processing of the data such as filtering and segmentation. In conclusion, one should note that the best way to improve the compatibility among overlapping strips is by implementing a rigorous calibration procedure.

Future research will focus on relating the detected discrepancies between overlapping strips to the system biases. Moreover, we will be using the estimated transformation parameters to remove the bias effect from the point cloud.

REFERENCES

Baltsavias, E., 1999. Airborne laser scanning: existing systems and firms and other resources, *ISPRS Journal of Photogrammetry and Remote Sensing*, 54 (2-3), pp. 164-198.

Bretar F., M. Pierrot-Deseilligny, and M. Roux, 2004. Solving the Strip Adjustment Problem of 3D Airborne Lidar Data. *Proceedings of the IEEE IGARSS'04,* 20-24 September, Anchorage, Alaska.

Crombaghs, M., E. De Min, and R. Bruegelmann, 2000. On the Adjustment of Overlapping Strips of Laser Altimeter Height Data. *International Archives of Photogrammetry and Remote Sensing*, 33(B3/1), pp. 230-237.

El-Sheimy, N., C. Valeo, and A. Habib, 2005. *Digital Terrain Modeling: Acquisition, Manipulation And Applications*, Artech House Remote Sensing Library, 257 p.

Filin, S., 2003. Recovery of systematic biases in laser altimetry data using natural surfaces. *Photogrammetric Engineering and Remote Sensing*, 69(11), pp. 1235–1242.

Huising, E. J., and L. M. G. Pereira, 1998. Errors and Accuracy Estimates of Laser Data Acquired by various Laser Scanning Systems for Topographic Applications, *ISPRS J. of Photogrammetry and Remote Sensing*, 53(5), pp. 245-261.

Kilian, J., N. Haala, and M. Englich (1996). Capture and evaluation of airborne laser scanner data. *International Archives of Photogrammetry and Remote Sensing*, 31(B3), pp. 383–388.

Kim C., Habib A., Mrstik P., 2007. New Approach for Planar Patch Segmentation using Airborne Laser Data. *Proceedings of the ASPRS 2007*, Tampa, Florida.

Maas, H. G., 2000. Least-Squares Matching with Airborne Laserscanning Data in a TIN Structure. *International Archives of Photogrammetry and Remote Sensing*, 33(B3/1), pp. 548-555.

Pfeifer, N., S. O. Elberink, and S. Filin (2005). Automatic Tie Elements Detection for Laser Scanner Strip Adjustment. *International Archives of Photogrammetry and Remote Sensing*, 36(3/W3), pp. 1682-1750.

Schenk, T., 2001. Modeling and Analyzing Systematic Errors in Airborne Laser Scanners, Technical Report in Photogrammetry No. 19, Ohio Sate University.

Vaughn, C. R., J. L. Bufton, W. B. Krabill, and D. L. Rabine (1996). Georeferencing of Airborne Laser Altimeter Measurements, *International Journal of Remote Sensing*, 17(11), pp. 2185-2200.

Vosselman, G., 2004. "Strip Offset Estimation Using Linear Features", http://www.itc.nl/personal/vosselman/papers/vosselman2002.columbus.pdf (accessed 15 Nov. 2007).

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