LIDAR Data for Photogrammetric Georeferencing

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Key words: laser scanning, photogrammetry, triangulation, linear-features, absolute orientation, registration.

SUMMARY

In a swiftly changing world, there is a growing demand for accurate information pertaining to physical surfaces for a variety of applications (e.g., automatic DEM generation, city modeling, and object recognition). For these purposes, 3D spatial data can be gathered from a number of diverse sources. In this regard, LIDAR and photogrammetric systems are receiving major attention due to their complementary characteristics and potential. An appealing feature of LIDAR is the direct acquisition of numerical 3D coordinates of object space points. The discrete and positional nature of LIDAR sets makes it difficult to derive surface semantic information, e.g., surface discontinuities and types of observed structures. In addition to that, reconstructed surfaces from LIDAR data possess no inherent redundancy. In aerial laser systems, LIDAR points are usually computed in the GPS reference frame, WGS84 for example, and consequently, it makes sense to reference the aerial images to the same system. In contrast to LIDAR systems, reconstructed surfaces from photogrammetric measurements possess rich semantic information that can be easily identified in the captured imagery. Moreover, reconstructed surfaces tend to be very accurate due to the inherent redundancy associated with photogrammetric intersection. The drawback of photogrammetric surface reconstruction is the significant time consumed by the process of manually identifying conjugate points in overlapping images (matching problem). On the other hand, automating the matching problem remains an unreliable task especially when dealing with large scale imagery over urban areas. Still, photogrammetric reconstruction of real surface requires enough control in the form of control points or other control features.

The complementary characteristics of both systems can be fully utilized only after successful registration of the photogrammetric and LIDAR data relative to a common reference frame. The registration methodology has to tackle the basic registration procedure components, mainly: registration features, mathematical function, and similarity assessment. This paper presents an approach for utilizing straight-line features derived from both datasets as the registration primitives. LIDAR lines are directly incorporated as control information in the photogrammetric triangulation. In addition to the registration approach, this paper displays two approaches for extracting linear features from LIDAR data with different and without post-processing. Also, this paper supports a comparison between the performance of photogrammetric analog and amateur digital cameras and its impact on the registration process. The performance analysis is based on the quality of fit of the final alignment between the LIDAR and photogrammetric models.

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1. INTRODUCTION

Different technologies have been recently developed for fast and reliable data collection over physical surfaces. Such developments were driven primarily by the growing demand by modern mapping applications such as city modeling, DEM generation, and object recognition. High quality digital imaging and LIDAR systems are examples of such evolving techniques. The new systems were accompanied by a vast increase in the volume and diverse characteristics of the collected data, a situation that needed efficient and reliable data handling and co-registration procedures. LIDAR and photogrammetric systems are receiving major attention due to their complementary characteristics and potential. LIDAR has the advantage of directly and accurately capturing digital surfaces. LIDAR systems are rapidly maturing on the hardware and supporting software levels. Lower price tag and increased accuracy of new LIDAR systems are causing an exponential availability of LIDAR datasets. An appealing feature of the LIDAR output is the direct acquisition of three dimensional coordinates of object space points. However, there is no inherent redundancy in reconstructed surfaces from LIDAR systems. Therefore, the quality of the derived information depends on the accuracy and the validity of the calibration parameters of the laser scanner, GPS, and INS components comprising the LIDAR system. Another characteristic of LIDAR surfaces is that they are mainly positional. In other words, only the 3D coordinates of points are collected without any further semantic information regarding the captured surfaces (e.g., material and type of observed structures) (Baltsavias, 1999).

Looking at the reconstructed surfaces from photogrammetric measurements, one can notice that such surfaces possess rich semantic information that can be easily identified in the array of acquired images. Moreover, inherent redundancy associated with the photogrammetric procedure allows for very accurate surface reconstruction. The negative aspect of photogrammetric surface reconstruction is the significant time consumed by the process of manually identifying conjugate points in overlapping images. On the other hand, automating the matching problem remains to be a difficult and unreliable task especially when dealing with large scale imagery over urban areas (Schenk and Csatho, 2002). Full utilization of the complementary characteristics of LIDAR and photogrammetric systems can be achieved by the integration of the acquired data. Such integration would lead to a complete surface description. The quality of the integration outcome unquestionably depends on the validity of the calibration parameters associated with each individual system and the accuracy of the co-registration process of the respective data (Postolov et al., 1999).

Legacy registration methodologies exploited point features for establishing the relation between two datasets. Such methodologies are not directly suitable for LIDAR surfaces since a laser footprint is rarely coincident with a distinct object point that can to be identified in the imagery (Baltsavias, 1999). Traditionally, surface-to-surface registration and comparison have been achieved by interpolating both datasets into a uniform grid. The comparison is then reduced to estimating the necessary shifts by analyzing the elevation differences at corresponding grid posts (Ebner and Ohlhof, 1994; Kilian et al., 1996). This approach has several limitations. First, the interpolation to a grid will introduce errors especially when dealing with captured surfaces over urban areas. Moreover, minimizing the differences between surfaces along the z-direction is only valid when dealing with horizontal planar surfaces (Habib and Schenk, 1999). Postolov et al. (1999) presented another approach, which works on the original scattered data without prior interpolation. However, the implementation procedure involves an interpolation of one surface at the location of conjugate points on the other surface. Additionally, the registration is based on minimizing the differences between the two surfaces along the z-direction. Schenk (1999) introduced an alternative approach, where distances between points of one surface along surface normals to locally interpolated patches of the other surface are minimized. Habib et al. (2001) implemented this methodology within a comprehensive automatic registration procedure. This procedure is based on processing the photogrammetric data to produce object space planar patches. This might not be always possible since photogrammetric surfaces provide accurate information along object space discontinuities while supplying almost no information along homogeneous surfaces with uniform texture.

In this paper an approach for the co-registration of LIDAR and photogrammetric surfaces relative to a common reference frame is introduced. Linear features are selected to efficiently represent and align LIDAR and photogrammetric datasets relative to the LIDAR reference frame. The following section addresses the general methodology and mathematical model of the suggested approach. In addition, we present different alternatives for the extraction of linear features from the LIDAR data. Section 3 outlines the experimental results from real datasets captured by LIDAR, analog/metric cameras, and digital/amateur cameras. Finally, the research conclusions and recommendations for future work are highlighted in Section 4.

2. CO-REGISTRATION METHODOLOGY

2.1 Introduction

A registration procedure is usually carried out to combine various datasets acquired by multiple sensors to achieve better accuracy and enhanced inference about the environment than can be reached through the use of one sensor. Generally, a registration methodology must deal with three issues. First, a decision has to be made regarding the common registration primitives. Second, one should establish a registration transformation function that mathematically relates the considered datasets. Third, a similarity measure should be found to guarantee the coincidence of conjugate primitives after applying the appropriate transformation function (Brown, 1992). The following sub-sections present a brief overview of the basic components of the registration process. Then, the techniques for the co-registration of photogrammetric and LIDAR datasets are presented.

2.2 Registration Primitives

Conjugate common primitives have to be identified and extracted from both datasets and then used to relate the datasets under consideration. The type of derived primitives greatly influences subsequent registration steps. Hence, it is fundamental to decide upon the appropriate primitives to be used for establishing the transformation between the datasets under consideration (Habib and Schenk, 1999). In registration problems involving spatial data, the three fundamental and most commonly used registration primitives are points, lines, and areal regions. Candidate features include road intersections, corners of buildings, rivers, coastlines, roads, lakes, and/or similar dominant man-made or natural structures. As mentioned earlier, it is almost impossible to link the laser footprint with the corresponding image point. However, at a higher processing cost, three intersecting LIDAR patches can be segmented and utilized to extract points, which can be then identified in the imagery. Such lengthy and inconvenient process surely excludes the point primitives from being appropriate as the registration primitives of choice. Accordingly, linear and areal features are the other candidate primitives that can be more suitable for datasets involving LIDAR data. As illustrated in Figure 1, for these primitives, the geometric distribution of individual points makes up the feature rather than individual occurrences.

Figure 1. Line and areas as clusters of individually measured points

Areal primitives (e.g., lakes, roofs, and homogeneous regions) can be extracted from LIDAR datasets using classification or segmentation algorithms. However, areal features are not suited for photogrammetric datasets since there are no established procedures for deriving object space areal features from corresponding features in the image space. Therefore, linear features are more appropriate than areal features due to their abundant availability in nature and the simplicity of the extraction algorithms. Moreover, the utilization of linear features allows for the consideration of areal features, which can be represented as a sequence of linear features along their boundaries.

Although, linear features can be represented either by an analytical function (e.g., straight lines, or parametric functions) or by a free form shape (Habib et al., 2002a), straight-line segments have been chosen as the registration primitives for the following reasons:

- Straight line features are abundantly available in urban and man-made objects.
- Detection of straight lines is easier in different datasets, and the correspondence problem between conjugate features becomes easier to solve.
- Straight line parameters can be accurately derived from the involved datasets.

– Similarity measures describing the correspondence of conjugate straight-line segments are simpler to establish.
– Straight lines segments can sufficiently represent free-form linear features.

After selecting straight-line segments as the registration primitives, one must decide on the representation and then the extraction methodologies of such lines from photogrammetric and LIDAR datasets.

The representation scheme of straight lines in the object and image space is central to the methodology for producing such features from photogrammetric datasets. Representing object space straight lines using two points along the line is the most convenient representation from a photogrammetric point of view since it yields well-defined line segments (Habib et al., 2002b). On the other hand, image space lines will be represented by a sequence of 2-D coordinates of intermediate points along the feature. This is an appealing representation since it can handle image space linear features in the presence of distortions as they will cause deviations from straightness. Furthermore, it will allow for the inclusion of linear features in scenes captured by line cameras since the imaging process of such cameras leads to deviations from straightness in image space linear features, which correspond to object space straight lines (Habib et al., 2002b). To be compatible with the representation of photogrammetric lines, LIDAR will be represented also by its two end points.

A set of conjugate linear features is to be extracted from both datasets to carry out the registration procedure. The derived LIDAR lines will be used as the source of the required control to align the photogrammetric model relative to the LIDAR reference frame. In this regard, one should note that the datum for the LIDAR data is established by the combination of high-quality GPS/INS units onboard the sensor platform. The extraction of straight-line features from both datasets is described in the following two subsections.

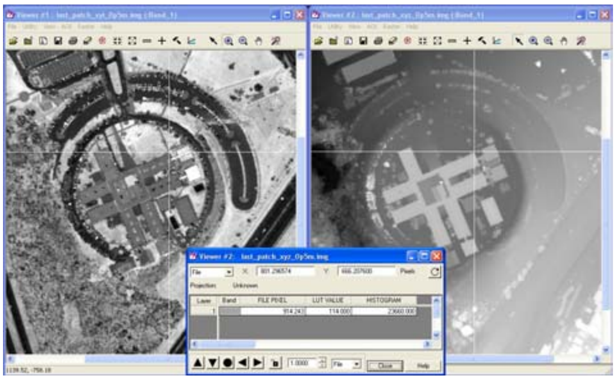
2.2.1 LIDAR Primitives

There are different approaches by which LIDAR lines can be collected. This work presents two alternative approaches. In the first approach, suspected planar patches in the LIDAR dataset are manually identified with the help of corresponding optical imagery, Figure 2. The selected patches are then checked using a least-squares adjustment to determine whether they are planar or not, and to remove blunders. Finally, neighboring planar patches with different orientation are intersected to determine the end points along object space discontinuities between the patches under consideration.

a) (b)

Figure 2. - Manually identified planar patches in the LIDAR data (a) guided by the corresponding optical image (b) in aerial dataset

Another simplified process for the extraction of LIDAR lines is to use the recorded intensity and range data direct measurement of linear features. Raw range and intensity data are first interpolated to a uniform grid using the same interpolation method and parameters, producing intensity and range images, Figure 3. Then, photogrammetric linear features are identified on the intensity image from which the planimetric coordinates of line ends are measured while observing height readings from the range image, Figure 3. It is worth mentioning that the interpolation method and applied parameters have a significant effect on the quality of the derived features.



(a) (b)

Figure 3. - Manually measuring planimetric coordinates from the intensity image (a) and height from the range image (b)

Many factors, including the availability of intensity data, play a role in the choice of the extraction method. Automatic extraction of straight lines is beyond the objectives of this study and will be investigated in future work. Following the extraction of straight-lines from both datasets, the focus will be shifted towards selecting a valid and proper transformation function that can faithfully represent the transformation between the involved datasets.

2.2.2 Photogrammetric Primitives

This section presents the methodology of incorporating tie linear features in photogrammetric triangulation. Manipulating tie straight lines, which appear in a group of overlapping images, starts with identifying two end points in one, Figure 4a, or two images, Figure 4b, along the line under consideration. These points will be used to define the corresponding object space line segment. It is worth mentioning that these points need not be identifiable or even visible in other images. Intermediate points along the line are measured in all overlapping images. Similar to the end points, the intermediate points need not be conjugate, Figure 4. The relationship between the image coordinates of the line end points $\{(x_{1'}, y_{1'}),\ (x_{2'}, y_{2'})\}$ and the corresponding ground coordinates $\{(X_1, Y_1, Z_1), (X_2, Y_2, Z_2)\}$ is established through the collinearity equations. Hence, four equations are written for each line. The intermediate points are included into the adjustment procedure through a mathematical constraint, which states that the vector from the perspective centre to any intermediate image point along the line is contained within the plane defined by the perspective centre of that image and the two points defining the straight line in the object space, Figure 5. For a given intermediate point,

i'', a constraint that indicates the points $\{(X_1, Y_1, Z_1)$, (X_2, Y_2, Z_2), (X''_O, Y''_O, Z''_O) and $(x_{i''}, y_{i''}, 0)\}$ are coplanar, is introduced and mathematically described by Equation 1.

$$\left(\vec{V}_1 \times \vec{V}_2\right) \bullet \vec{V}_3 = 0 \tag{1}$$

Where:

$\vec{V}_1$ is the vector connecting the perspective centre to the first end point of object space line,
$\vec{V}_2$ is the vector connecting the perspective centre to the second end point of object space line,
$\vec{V}_3$ is the vector connecting the perspective centre to an intermediate point i'' along the corresponding image line.

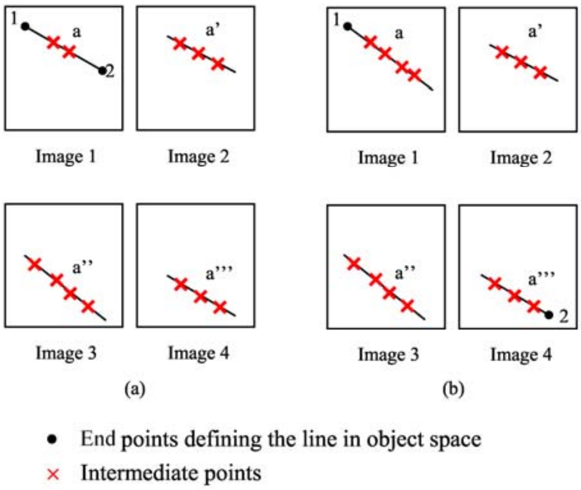


Figure 4. End points defining the object line are either measured in one image (a) or two images (b)

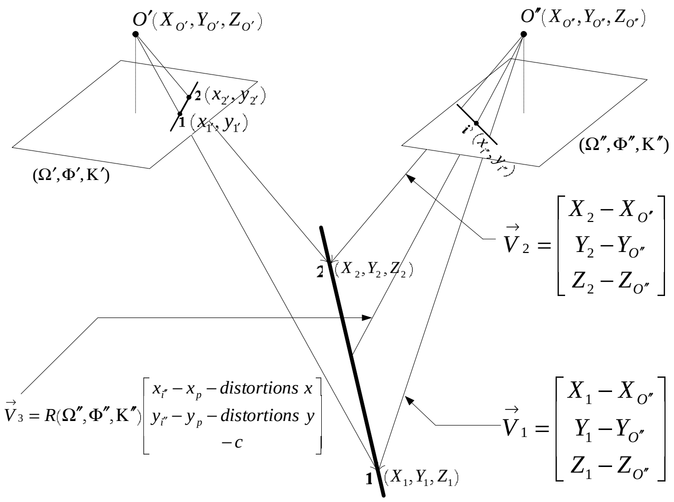


Figure 5. Perspective transformation between image and object space straight lines and the coplanarity constraint for intermediate points along the line

It is important to note that the three vectors in Equation 1 should be represented relative to a common coordinate system (e.g., the ground coordinate system). The constraint in Equation 1 incorporates the image coordinates of the intermediate point, the Exterior Orientation Parameters (EOP), the Interior Orientation Parameters (IOP) including distortion parameters, as well as the ground coordinates of the points defining the object space line. Such a constraint does not introduce any new parameters and can be written for all intermediate points along the line in overlapping imagery. The number of constraints is equal to the number of intermediate points measured along the image line.

In some applications, the lines can be used as control features instead of being regular tie lines. In this situation, the object coordinates of line end points are known, hence, these points need not be measured in any of the images. Consequently, image space linear features are represented only by a group of intermediate points measured in all images.

2.3 Transformation Function

The selection of the type of spatial transformation or mapping function needed to properly overlay the two datasets is considered as the most fundamental problem of any registration technique. In this study, a global 3-D similarity transformation (conformal transformation) is used, Equation 2, as the registration transformation function. As the name suggests, this type of transformation preserves the geometric similarity where the angles are maintained and distances are changed with the same ratio, the scale factor. In other words, this transformation defines rigid-body transformation where the true shape is retained. One should note that this transformation assumes that the photogrammetric and LIDAR systems are well calibrated (i.e., there are no systematic errors that have not been compensated for). However, the presence of systematic errors, which cannot be modeled by rigid-body transformation, will manifest itself in a poor quality of fit between the involved datasets following the registration procedure.

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} + S\ R(\Omega,\ \Phi,\ \mathrm{K}) \begin{bmatrix} X_a \\ Y_a \\ Z_a \end{bmatrix} \qquad (2)$$

where

S is a scale factor,

$(X_T\ Y_T\ Z_T)^T$ is the translation vector between the origins of the photogrammetric and LIDAR coordinate systems,

$R(\Omega,\Phi,\mathrm{K})$ is the 3-D orthogonal rotation matrix between the two coordinate systems,

$(X_a\ Y_a\ Z_a)^T$ are the photogrammetric coordinates of a given point, and

$(X_A\ Y_A\ Z_A)^T$ are the coordinates of the corresponding LIDAR point relative to the LIDAR reference frame.

2.4 Similarity Measure

Finally, the similarity measure is intended to introduce the necessary constraints for ensuring the coincidence of conjugate photogrammetric and LIDAR primitives after applying the proper transformation function. The formulation of the similarity measure depends on the selected registration primitives and their respective attributes (i.e., representation scheme). In

addition, the similarity measure depends on the utilized methodology for incorporating the LIDAR and photogrammetric data in the registration process.
As it has been mentioned earlier, the registration primitives, straight-line segments, will be represented by their end points. One should note that the end points of corresponding photogrammetric and LIDAR lines need not be conjugate. As for the processing methodology, LIDAR linear features are used as the source of control and are directly incorporated in the photogrammetric bundle adjustment (i.e., the LIDAR features will establish the datum for the photogrammetric model). The similarity measure should mathematically ensure that the projected LIDAR lines onto the image space coincide with the corresponding image lines. This is described by the coplanarity constraint expressed in Equation 1. In this processing scenario, the image space features will be represented by a sequence of intermediate points. The end points defining the object space line will not be measured in the imagery since they are already provided by the LIDAR data. One should also note that the 3-D similarity transformation, Equation 2, is implicitly included within the photogrammetric adjustment. It is important to note that at this stage the correspondence between linear features in photogrammetric and LIDAR data is established manually. Automatic identification of conjugate line segments will be the focus of future research.

So far, we have addressed the three basic components of the registration methodology. First, straight line segments are chosen as the registration primitives. Second, a 3-D similarity transformation is utilized as the registration transformation function. This transformation assumes the absence of any biases, which cannot be modeled by rigid-body transformation, in the involved photogrammetric and LIDAR systems. Third, the similarity measure is formulated based on the selected primitives, transformation function, and processing methodology. The performance of these components will be evaluated in the experimental result section using real data that have been captured by a professional analog camera, an amateur digital camera, and a high end LIDAR system.

3. EXPERIMENTAL RESULTS

A set of experiments are designed to serve the initial goals setout at the beginning of this paper which span the following objectives:

- The feasibility of using straight-line segments for the co-registration of LIDAR and photogrammetric data.
- Comparative analysis of the performance of different extraction approaches of linear features from the LIDAR data. The first approach utilizes the raw LIDAR data for plane fitting followed by an intersection procedure. The second approach uses interpolated range and intensity images for an easier identification of the LIDAR linear features.
- Comparative analysis of the influence of different interpolation techniques on the quality of the extracted linear features from the intensity and range images.
- Comparative analysis of the performance of professional analog and amateur digital cameras.

The performance in each experiment will be judged by the quality of fit between conjugate features after the registration procedure and/or check point analysis.

3.1 Datasets and Processing Steps

This study involved two photogrammetric and one LIDAR datasets. Table 1 summarizes the properties of the photogrammetric datasets (scanned analog images captured by a professional analog camera – RC-10 and digital images captured by an amateur digital camera – SONY-F717). The table also shows expected horizontal and vertical accuracy from each dataset considering the pixel size, image coordinate measurement accuracy, image scale, and height-base ratio. The LIDAR dataset was captured using an OPTECH ALTM 2050 laser scanner with an average flying height of 975m and mean point density of 2.24 points/m^2 (~0.7m point spacing). The range and intensity data were recorded. According to the sensor and flight specifications, 0.5m horizontal and 0.15m vertical accuracies are expected.

Table 1: Specifications of the photogrammetric datasets

Camera type & model	RC-10 analog	SONY-F717 digital
Focal length (mm)	153.167	11.6761
# of images	6	17
# of control points	54	31
Avg. flying height (m)	975	737
Avg. base (m)	540	221
Pixel size (mm)	0.024	0.004
Image measurement accuracy (mm)	± 0.024	± 0.004
Expected accuracy (assuming one pixel measurement error)		
planimetric (m)	0.15	0.25
vertical (m)	0.39	1.19

Tie and control points as well as linear features are measured in the image blocks. These measurements are incorporated in several bundle adjustment experiments. The datum of the photogrammetric model has been established by using either control points, which have been collected by geodetic measurements, or control lines from the LIDAR data. The outcome from the bundle adjustment includes the EOP of the involved imagery, the ground coordinates of the tie points, and the ground coordinates of the end points defining the tie lines. In the mean time, LIDAR features have been extracted using two approaches. The first approach utilizes the raw range data to identify neighboring planar patches, which are then intersected. The second approach manipulates interpolated range and intensity images to identify the corresponding linear features. For the second approach, two sets of range and intensity images are generated from the raw LIDAR points using two interpolation schemes, which will be denoted I_1 and I_2, respectively. I_1 is based on a pixel size of 0.3m and 4m-radius search window while using 2^{nd} degree inverse distance weighting. On the other hand, I_2 is based on 1.0m pixel size using the nearest neighbor interpolation technique.

In these experiments, extracted linear features from the interpolated intensity and range imagery are used directly in the photogrammetric triangulation. Due to limitations in identifying a sufficient number of neighboring planar patches over the entire area, linear features from patch intersection are not enough for establishing a proper datum for the photogrammetric adjustment.

3.2 Experiments Involving Analog Imagery and LIDAR

Extracted straight-line segments from the interpolated LIDAR datasets (I_1 and I_2) are used in separate experiments as the source of control for the photogrammetric triangulation of the RC-10 image block. Table 2 summarizes the quality of the aligned photogrammetric model through check point analysis. More specifically, the photogrammetric coordinates of the check points are compared with these derived from independent geodetic measurements. The comparison results in Table 2 include the average difference between the photogrammetric and geodetic coordinates together with the corresponding standard deviation.

Table 2: Check point analysis for LIDAR/RC-10 datasets

	LIDAR set I_1	LIDAR set I_2
# of control lines	80	79
# of check points	32	32
ΔX (m)	0.75 (±0.51)	0.65 (±0.28)
ΔY (m)	-0.10 (±0.43)	-0.15 (±0.26)
ΔZ (m)	-0.75 (±0.36)	-0.69 (±0.42)

3.3 Experiments Involving Digital Imagery and LIDAR

Similar to the previous experiments, extracted straight-line segments from the two LIDAR datasets (I_1 and I_2) are used in separate experiments as the source of control information for the photogrammetric triangulation of the SONY-F717 image block. Table 3 summarizes the quality of the aligned photogrammetric model through check point analysis.

Table 3: Check point analysis for LIDAR/SONY-F717 datasets

	LIDAR set I_1	LIDAR set I_2
# of control lines	68	68
# of check points	31	31
ΔX (m)	0.38 (±0.63)	0.42 (±0.70)
ΔY (m)	0.35 (±0.70)	0.20 (±0.67)
ΔZ (m)	-0.49 (±1.11)	-0.51 (±1.12)

3.4 Results

A categorized set of remarks can be recorded when comparing the results in Tables 2 and 3:
Digital/analog comparison

- Based on the standard deviations associated with the check points, the RC-10 data is showing better alignment when compared to the SONY data. This should come as no surprise since the expected accuracy from the RC-10 is superior to that from the SONY (refer to Table 1).

Analog imagery/LIDAR interpolation comparison

- Based on the standard deviations associated with the check points, the RC-10 is showing a better alignment when using linear features from the I_2 dataset in place of these derived from I_1. This is expected since the point spacing in I_2 (1.0m) is closer to the point spacing associated with the raw LIDAR points (0.7m). In other words, I_2 is a more realistic sampling considering the raw point density. Thus, the interpolation method and the interpolated grid size should be selected to be commensurate with the raw LIDAR data.
- Comparing the mean and the corresponding standard deviations from the check point analysis, one can identify a persistent bias in the X and Z directions (i.e., the mean value is significantly larger than the standard deviation). After thorough investigation, it was found that the available control points are given relative to the SAD 69 reference frame prior to 1998. On the other hand, LIDAR data was based on the SAD 69 after the 1998's adjustment. Certain biases, especially in the *X*- and *Z*-directions, have been reported between the two versions.

Digital imagery/LIDAR interpolation comparison

- Based on the standard deviations associated with the check points, the SONY data is showing almost identical alignment quality when using LIDAR features derived from the I_1 and I_2 datasets. This is expected since the photogrammetric errors for the SONY block (Table 1) are more dominant than the errors in the derived LIDAR linear features using different interpolation techniques. Again, the results for this comparison hint but do not confirm the presence of biases in the X and Z directions (and even Y direction) since the standard deviation is significantly larger than the mean value.

4. CONCLUSIONS AND FUTURE WORK

In this paper a registration methodology for the alignment of LIDAR and photogrammetric models relative to a common reference frame using straight-line features was presented. The straight-line segments have been chosen as the registration primitives since they can be reliably extracted from the photogrammetric and LIDAR data. A 3D similarity transformation has been selected as the transformation function relating the datasets in question. This transformation assumes the absence of biases, which cannot be modeled by rigid-body transformation, between the LIDAR and photogrammetric datasets. Also, appropriate similarity measures have been introduced to ensure the coincidence of the photogrammetric and LIDAR features after applying the registration transformation function. The similarity measure was implemented through directly incorporating the LIDAR features as a source of control in the photogrammetric bundle adjustment. In addition to the registration

methodology, we presented two techniques for the extraction of linear features from LIDAR data. The first technique utilized the raw LIDAR data to identify neighboring planar patches, which are then intersected to produce the linear features. The second technique, utilized interpolated intensity and range images for an easier extraction of the linear features.
To test the feasibility of the developed methodologies, several experiments were conducted using real data captured by an analog professional camera (RC-10), an amateur digital camera (SONY-F717), and a high end LIDAR system (OPTECH ALTM 2050). The outcome from these experiments suggests the following:

- It is sufficiently feasible to use straight line features in establishing a common reference frame for the LIDAR and photogrammetric surfaces.
- As expected, the quality of derived the LIDAR and photogrammetric features plays an important role in the quality of the final fit between the respective models. In this regard, the following has been observed:
- Linear features from the analog RC-10 data exhibit higher quality when compared to these derived from the SONY-F717 data. This should be expected due to the better height-base ratio associated with the RC-10 image block.
- Derived LIDAR linear features from the interpolated range and intensity images show better quality if the sampling interval of the produced imagery is commensurate with the point density of the raw LIDAR data.
- The quality of the derived LIDAR linear features influences the quality of the registration if the photogrammetric features exhibit a commensurate or better quality.
- The registration methodology is capable to give a clue about the presence of biases and systematic errors between the involved datasets.
- Future research work will address the automation of the extraction of linear features from photogrammetric and LIDAR data together with the correspondence between conjugate features. Also, we will be looking at the possibility of developing new visualization tools for an easier portrayal of the registration outcome. Overlay of the derived ortho-photos and LIDAR data, Figure 6 can be used to check the quality of the registration process as well as showing the different characteristics of the involved datasets. Finally, registered multi-temporal datasets will be inspected for the possibility of developing automatic change detection techniques. For example, Figure 7 shows the presence of object space changes between the ortho-photos derived from RC-10 and SONY-F717 imagery, which have been captured at different epochs.

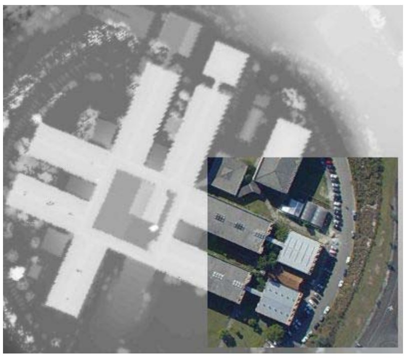


Figure 6. A part of a LIDAR intensity image is overlaid by a patch from the SONY-F717 ortho-photo.

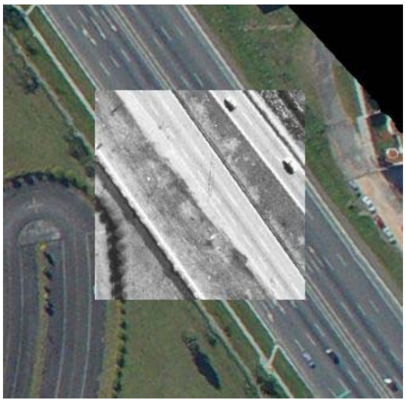


Figure 7. Observed changes between the RC-10 (foreground) and SONY-F717 (background) ortho-photos (Note that the road has been widened in the SONY ortho-photo).

REFERENCES

Baltsavias, E., 1999. A comparison between photogrammetry and laser scanning. **ISPRS Journal of Photogrammetry & Remote Sensing**, 54(1):83–94.

Brown, L., 1992. A survey of image registration techniques, **ACM Computing Surveys** 24(4): 325-376.

Habib, A., T. Schenk, 1999. New approach for matching surfaces from laser scanners and optical sensors, **The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences**, 32(3W14):55-61.

Habib, A., Y. Lee, and M. Morgan, 2001. Surface matching and change detection using the modified Hough transform for robust parameter estimation. **Photogrammetric Record Journal,** 17(98): 303-315.

Habib, A., Y. Lee, M. Morgan, 2002a. Bundle adjustment with self-calibration using straight lines. **Photogrammetric Record Journal,** 17(100): 635-650.

Habib, A., S. Shin, M. Morgan, 2002b. *New approach for calibrating off-the-shelf digital cameras*. In **ISPRS Commission III Symposium "Photogrammetric Computer Vision**", Graz, Austria, September 9 – 13, 2002.

Ebner, H., and T. Ohlhof, 1994. Utilization of ground control points for image orientation without point identification in image space. In **The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences**, 30(3/1):206–211.

Kilian, J., N. Haala, and M. Englich, 1996. Capture and evaluation of airborne laser scanner data. In **The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences**, 31(B3):383-388.

Postolov, Y., A. Krupnik, and K. McIntosh, 1999. Registration of airborne laser data to surfaces generated by photogrammetric means. In **The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences**, 32(3W14):95-99.

Schenk, T., and B. Csathó, 2002. Fusion of LIDAR data and aerial imagery for a more complete surface description. In **The International Archives of Photogrammetry and Remote Sensing and Spatial Information Sciences**, 34(3A):310-317.

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