REGISTRATION OF AIRBORNE LASER DATA TO SURFACES GENERATED BY PHOTOGRAMMETRIC MEANS

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ABSTRACT

Laser altimetry has provided a source of elevation information, which is both accurate and spatially dense. This information is beneficial for the production of visible surface models, especially in areas where traditional photogrammetric methods are unable to provide accurate heights. Although laser altimetry has many benefits, it also has limitations due to its lack of thematic information and due to calibration errors that may occur during data acquisition. Therefore, it would be beneficial to use both laser data and photogrammetric data to achieve the best results. To work with both data sets simultaneously, it must be ensured that the data sets are accurately registered. The research presented in this paper describes an algorithm developed specifically for registering surfaces acquired using different methods, and in particular, laser altimetry and photogrammetry.

The surface registration algorithm uses the difference in elevation between the surfaces and the gradients of the surfaces to produce observation equations. These are solved using an iterative least-squares adjustment. The transformation parameters that are determined by the algorithm include scale, translations and rotations. Testing was undertaken to assess the capabilities of the algorithm. Initial tests were carried out using synthetic data sets with known transformations. Further testing was undertaken using airborne laser data and aerial imagery covering an urban site located at Ocean City, Maryland. The results of the testing with this data set showed a systematic error in the location of the laser data as compared to the photogrammetric data. This paper details the approach taken, including the presentation of the equations used to determine the relevant transformation parameters, and the results of the initial experimentation.

1 INTRODUCTION

Airborne laser altimetry provides accurate surface points for obtaining a digital surface model (DSM). The trend towards using laser altimetry is motivated by the high spatial frequency of the data, the efficiency of the data capture, and the minimal data processing required. Laser altimetry has benefits as it can provide measurements in areas where traditional photogrammetric techniques encounter problems. Such areas include urban areas, wooded areas and areas that produce little or no texture or contrast in the digital imagery being used. Following this determination, laser data can be considered as complementary to photogrammetric techniques and would provide benefits when combined with data obtained from these methods. This approach has been suggested recently by many researchers (Ackermann, 1999; Axelsson, 1999; Baltsavias, 1999; Brenner, 1999; Csathó *et al.*, 1999; Fritsch, 1999; Haala, 1999; Haala and Anders, 1997; Toth and Grejner-Brzezinska, 1999; and Vosselman 1999).

Utilizing data from both laser altimetry and photogrammetry requires that the two data sets relate to the same coordinate system. To ensure this is the case, the surfaces generated from the data sets must be registered as accurately as possible. The algorithm presented in this paper is specifically designed for registering surfaces derived from laser data and photogrammetric data.

The transformation parameters between two surfaces, which both contain irregularly distributed points, are determined without requiring the surfaces to be interpolated to a regular grid. These parameters represent a three-dimensional conformal transformation, and include scale, translations and rotations. Observation equations are based on the difference in elevation between the surfaces and the local gradients. The parameters are estimated using an iterative least-squares solution.

Testing was undertaken to assess the capability of the algorithm to accurately register two surfaces. Initial tests were carried out using synthetic data sets with known transformations. These tests were useful to show the validity of the algorithm, and also to eliminate any implementation flaws. The sensitivity of the algorithm to random errors was investigated by introducing such errors to the data sets. Further testing has been undertaken using airborne laser data and aerial imagery covering an urban site over Ocean City, Maryland.

In section 2, the suggested approach is described in detail, together with the mathematical model. Section 3 presents the results obtained so far. Results from both synthetic and real data experiments are shown.

2 MATHEMATICAL BACKGROUND OF THE PROPOSED SURFACE MATCHING PROCEDURE

The aim of the surface matching procedure is to register the airborne laser data to the surface generated by photogrammetric means, thus allowing the surfaces to be transformed to a common coordinate system. The most common methods for determining the orientation parameters between two data sets are based on conjugate points. These methods are not applicable when using airborne laser data as the laser measurement is referring to a footprint, and not to a specific point which can be identified on the ground (Baltsavias, 1999). The similarity between the height information within a surface (and a laser surface in particular) and the intensity values in imagery allows the concepts from image matching methods to be used in developing a suitable algorithm for surface matching (Kilian *et al.*, 1996).

The mathematical formulation is derived by dividing the transformation into two steps, i.e., horizontal and vertical. The latter also includes leveling parameters. A similar approach is taken in the absolute orientation procedure in traditional photogrammetry (Kraus, 1993). Let a target surface be represented by n irregular distributed points with coordinates (x',y',z'), and a source surface be represented by m irregular distributed points with coordinates $(x",y",z")$. These two surfaces represent the same real surface, but they may have been captured by different methods, which might introduce some systematic errors between the two data sets. The problem is to determine the transformation parameters required for transforming the source surface into the coordinate system of the target surface.

The horizontal transformation between the two surfaces may be described by two horizontal shifts, a rotation parameter and a scale factor. Each point from the target surface may be transformed to the source surface by these parameters. The coordinates in the source surface are calculated by

$$\begin{pmatrix} x" \\ y" \end{pmatrix} = m \cdot \begin{pmatrix} \cos\kappa & \sin\kappa \\ -\sin\kappa & \cos\kappa \end{pmatrix} \cdot \begin{pmatrix} x' \\ y' \end{pmatrix} + \begin{pmatrix} \Delta X \\ \Delta Y \end{pmatrix} \qquad (1)$$

where $\Delta X, \Delta Y$ are the horizontal shift parameters, κ is the horizontal rotation and m is the scale factor.

Once a horizontal transformation has been performed, the elevation shift ΔZ and leveling slopes a,b are introduced, to relate the two surfaces by

$$z'(x',y') = ax' + by' + z"(x",y") + \Delta Z. \qquad (2)$$

The differences between the two surfaces in the case described here are assumed relatively small. In particular, small leveling angles are assumed. Based on this assumption, Equation 2 is rewritten as

$$z'(x',y') = d\varphi x' + d\omega y' + z"(x",y") + dZ, \qquad (3)$$

where $d\varphi, d\omega$ are the small leveling angles.

The planar coordinates $(x",y")$ from Equation 1 may be substituted into the right hand side of Equation 3 and in this way, the relationship between the height differences and the planar orientation parameters is established. Assuming further that the horizontal rotation is also small, and that the scale factor is close to 1, provides the following expression:

$$z'(x',y') = d\varphi x' + d\omega y' + dZ +$$
$$+ z"\left(\left\{\begin{bmatrix} x' \\ y' \end{bmatrix} + \begin{bmatrix} dm & d\kappa \\ -d\kappa & dm \end{bmatrix} \cdot \begin{bmatrix} x' \\ y' \end{bmatrix} + \begin{bmatrix} \Delta X \\ \Delta Y \end{bmatrix}\right\}^T\right). \qquad (4)$$

As can be clearly observed, this mathematical model is not linear, and therefore must be linearized in order to be solved in a standard least-squares method. Applying a Taylor series to the equation above, a linear observation equation for each point of the source surface is given by

$$\Delta z = z' - z" =$$
$$\begin{bmatrix} x & y & 1 & \frac{\partial z}{\partial x}y - \frac{\partial z}{\partial y}x & \frac{\partial z}{\partial x}x + \frac{\partial z}{\partial y}y & \frac{\partial z}{\partial x} & \frac{\partial z}{\partial y} \end{bmatrix} \cdot \qquad (5)$$
$$\begin{bmatrix} d\varphi & d\omega & \Delta Z & d\kappa & dm & \Delta X & \Delta Y \end{bmatrix}^T$$

It can be observed that the elevation differences between the two surfaces are considered as observations, while gradients are required for forming the design matrix.

The gradients are calculated by reconstructing a small surface patch around a point in the target surface, using a planar or bilinear surface generation approach, avoiding the need to interpolate neither of the surfaces to a regular grid. The decision concerning which surface to use is based on an analysis of the surface residuals. If large residuals are obtained by reconstructing the small surface, a higher order surface is sought.

Using the described approach, it is clear that in some circumstances not all the seven parameters can be accurately determined, due to high correlation among them. The number of parameters that can be determined depends mainly on surface geometry. In the case of matching two horizontal planes for instance, only a difference in height may be determined. The decision about which parameters to set is based on an analysis of the variance-covariance matrix and the surface spectrum. A discussion about such analysis is left for another paper.

It should be noted that the proposed algorithm is suitable for surfaces with relatively moderate slopes. Areas with steep slopes should be eliminated from the calculations as laser measurements in these areas may be affected by large errors.

3 EXPERIMENTAL RESULTS

Experiments were conducted by applying the matching algorithm to both synthetic and real data. Using a synthetic data set, where the 3D transformation between the two surfaces is known, allows the elimination of any implementation flaws. Using real data indicates the capability of the algorithm to actually determine the transformation parameters between a laser surface and a surface generated by photogrammetric means.

3.1 Experiments with synthetic data

The synthetic data used for the experiments consists of a surface with a known parametric function, as shown in Figure 1. A large number of randomly distributed points on this surface were calculated to represent a target surface. These points are represented in Figure 1 as a triangular network. To simulate the affect of errors on the data, random noise was added to the elevations of these points. Another smaller set of 30 randomly distributed points was created in the same manner, which constitutes the source surface. These points were shifted and rotated by selected parameters, and therefore it was possible to check the quality of the parameters resulted from the surface matching algorithm. The surface gradients were extracted from the target surface by calculating local bilinear surface parameters.

A stable solution for all selected sets of parameters was obtained within 3-4 iterations of the adjustment procedure. The determined values of the parameters were similar to those used for simulating the transformation of the source surface. The elevation differences between points on the transformed source surface and the target surface were smaller than the noise that was added initially to the target surface.

In another test with the synthetic data, the influence of large errors in some points of the source surface was assessed when no efforts were made to recognize or eliminate the outliers. It was found that outliers in one or two points on the source surface do not affect the ability of the algorithm to determine the correct parameters.

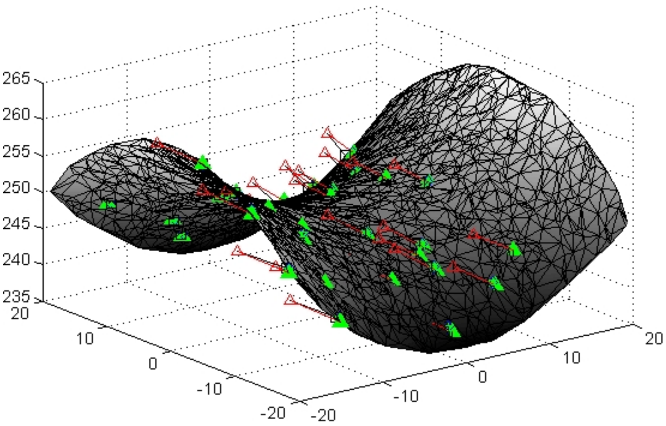

Figure 1: Synthetic test data.

3.2 Experiments with real data

Further testing was undertaken using airborne laser data and aerial imagery covering an urban site in Ocean City, Maryland. These data contain points acquired by the Airborne Topographic Mapper (ATM) laser system and panchromatic aerial photography from NGS. The ATM is a conical scanning laser altimeter developed by NASA for precise measurement of surface elevation changes in polar ice sheets, ocean beaches and drainage systems. The instrument combines high pulse rate with a scanning capability.

Figure **2** shows part of an aerial image that was taken as a test area. For this testing, planar surfaces of sloped roofs were measured manually on a digital photogrammetric workstation. Several combinations of these segments were used as the target surface. The results of this testing are shown here using two of these sets. The first set contains one row of buildings and the second set contains two parallel rows of buildings.

Each planar segment was defined as a mathematical surface, which was determined using a least-squares adjustment. For each segment, the appropriate points from the laser data set were found and elevation differences between the laser points and the roof segment were used as observations. The mathematical formulation enables the calculations of both these elevation differences and the gradients required for performing the matching procedure

Figure 3 shows the laser points overlaid on the planar roof segments. A histogram of the height differences between the roof segments and the laser points was created, as shown in Figure 4. The relatively large average difference in elevation between the two data sets can be clearly observed. The histogram also shows the existence of outliers. These outliers are actually points on the ground, which have been mistakenly included in the areas being matched. The outliers were eliminated using a median filter with respect to the expected laser precision. The threshold is marked on the histogram by a pair of vertical lines.

The algorithm described in Section 2 was applied to this data set. Due to the geometric characteristics of the surface (the set of roof planes), only three shifts can be determined accurately. The laser points were transformed using the determined parameters, and are shown in Figure 5. The respective histogram of the elevation differences is shown in Figure 6. It can be seen that the systematic shift of the elevations has been eliminated.

The results for the second set, which covers a larger area, are shown in Figures 7-10. It can be seen that the systematic error is similar to the smaller set, i.e., it is consistent over the area. Figures 9 and 10 that the transformation was recovered in this case as well.

Estimation of the accuracy of the parameters showed that their standard deviation is better than 10 cm both in horizontal and vertical directions. An elevation difference of approximately 110 cm in elevation (consistent with the visual inspection of the histogram) and 40 cm in flight direction have been found. As mentioned earlier, no attempt has been made at this stage to analyze the source of these errors.

Figure 2: Image coverage of the test area.

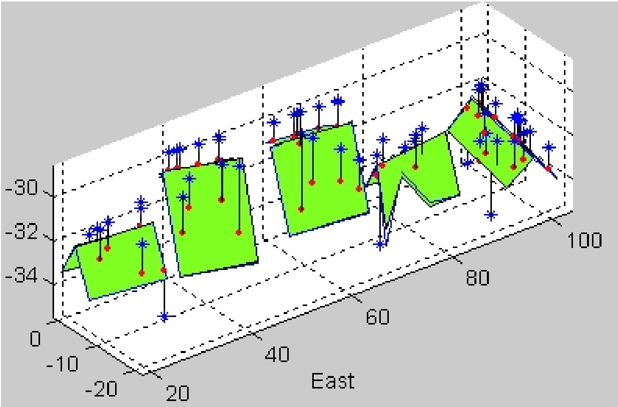

Figure 3: Laser points and planar roof segments before transformation (first set).

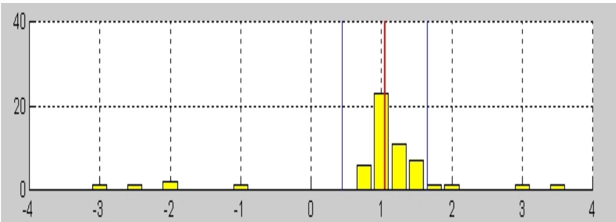

Figure 4: Elevation differences between laser points and measured planar roof segments before transformation (first set).

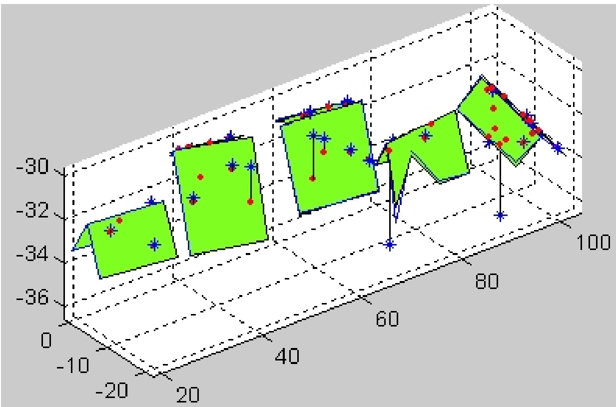

Figure 5: Laser points and planar roof segments after transformation (first set).

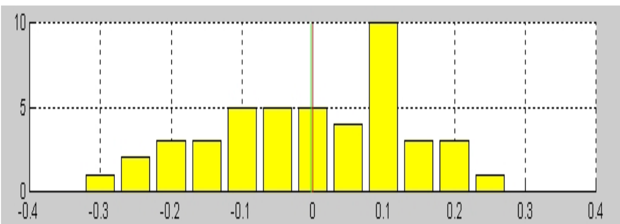

Figure 6: Elevation differences between laser points and measured planar roof segments after transformation (first set).

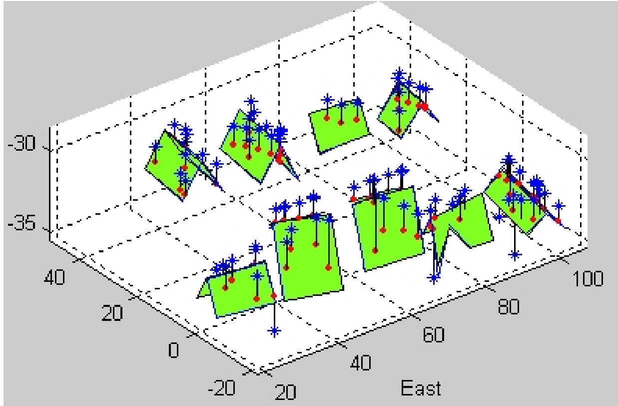

Figure 7: Laser points and planar roof segments before transformation (second set).

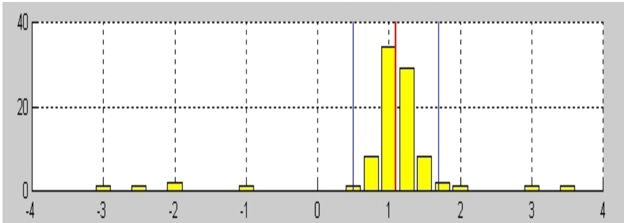

Figure 8: Elevation differences between laser points and measured planar roof segments before transformation (second set).

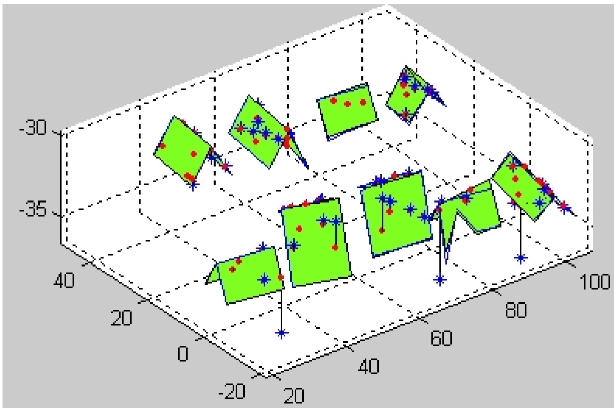

Figure 9: Laser points and planar roof segments after transformation (second set).

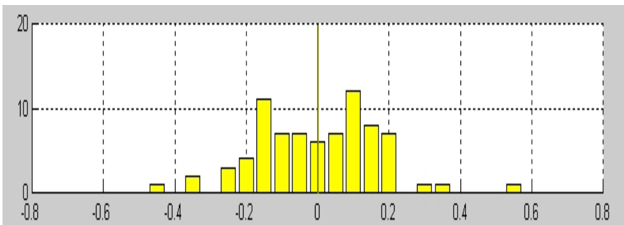

Figure 10: Elevation differences between laser points and measured planar roof segments after transformation (second set).

4 SUMMARY

Laser scanning is a novel approach for measuring surface elevations, from which digital surface models can be extracted easily and efficiently. However, laser measurements may suffer from systematic errors and from errors occurring near surface discontinuities. Integration of laser data with information available from aerial images is expected to render better surfaces.

In order to integrate these two sources of information, they must be related to the same coordinate frame. A method developed for matching two surfaces and transforming one to the other has been presented. The method was tested both with synthetic and with real data and found stable and accurate.

While testing the method, systematic differences between the two surfaces have been found. Future work should concentrate on analyzing the possible sources for these differences. Further work is also required in the area of analyzing surface characteristics for determining what transformation parameters can be calculated using the described algorithm.

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