STOCHASTIC ASSESSMENT OF TERRESTRIAL LASER SCANNER MEASUREMENTS TO IMPROVE DATA REGISTRATION

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ABSTRACT

The registration of point clouds that are acquired from multiple viewpoints is a fundamental task for laser scanner data processing. To register the simultaneous adjacent scans, every scan has special targets attached onto the object(s) like plain retro-reflective, black-white targets as well as such targets, which have well-known geometrical 3D shapes (e.g. spheres, planes, cylinders, etc.). These targets or shapes are used as landmarks and their 3D centre coordinates are modelled from the laser scanner point clouds in a local coordinate system.

To transform all the adjacent scans to a reference scan, the least squares solution was used as a fitting algorithm to find the parameters of the model transformation. Although, realistic stochastic modelling for data registration is still a difficult task to accomplish in practice, both functional and stochastic models need to be carefully defined. In this paper the mixed least square solution was used to calculate the transformation parameters. Using this model, the coordinates of registration targets in left and right scans are considered as observations. The advantage of this approach is giving the same registration target different weights in every two adjacent scans. A stochastic assessment procedure has been developed to take into account the range between the scanner and the registration targets in the left and right scan.

A comparison between current study results and other commercial available software (Cyclone 5.1, Australis and Panda) indicated that the reliability of the estimated transformation parameters between the adjacent scans is improved.

INTRODUCTION

High resolution tripod-mounted laser scanners are used for architecture, virtual reality, heritage documentation, preservation and lots of civil engineering applications. The market offers a lot of terrestrial laser scanners with (TLS) different system specifications. 3D laser scanners are classified into different ways, but all the scanner are very similar to the reflector less total station. Each surveying project can be divided into three major steps: data acquisition, data processing and data visualization. Most of the projects will be scanned in several scans that must be put together in a common reference coordinate system. The term registration or matching are used to describe the same task; the registration of each scan into a predefined coordinate system is usually performed by using ground control points (GCPs) which used in Photogrammetric method. Depending on economical, manufacturer, technical or practical reasons, (TLS's) data could be registered by one of the following methods:

1. For registration to a predefined coordinate system:
   - fix the coordinates of the registration targets from total station ground coordinate system (GCPs) and transform the local coordinates of every scan to it. The disadvantage of this method is using an extra instrument (total station) which will raise the cost of the projects.
2. For registration to a local coordinate system, If there are tie points available
   - Fix the coordinate system for the first scan and transform all the neighbouring scans into the first one. But all the scans must be overlapped. The main drawback of the second method is that scans must overlapped

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in a large part, but it is preferable in some applications where the registration targets using (GCPs) are difficult to achieve. If there is no set of tie points from the later case, many techniques could be used to calculate transformation parameters and these techniques depend on whether a set of tie points available or not.

If there are no tie points available, establishing a set of corresponding points from two data sets can be used (J. Besl et al., 1992). Another technique (Dijkman et al., 2002) by matching different surface models. With these two techniques all the scans must be overlapped during scanning step. None of the two techniques is designed to register data simultaneously. If we have a set of tie points or registration targets the least squares could be used to calculate the transformation parameters. The least squares solution provides a set of quality parameters for the unknowns which measure the goodness of the fit.

Laser Scanners are spherical measurement systems that measure the area of interest with a very high frequency. For each point one oblique distance $\rho$ and two orthogonal angles $\theta$ and $\alpha$ are measured, together with the additionally registered intensity of the returning signal distance. Each point is described in a three dimensional local coordinate system. The geometric relation between these measurements and three-dimensional information of the scanning points can be calculated from equation 1.

$$
\begin{bmatrix}
  x \\
  y \\
  y
\end{bmatrix} = \begin{bmatrix}
  \sin \theta \sin \alpha \\
  \cos \theta \sin \alpha \\
  \cos \alpha
\end{bmatrix}
\rho
$$

(1)

where $x$, $y$, and $z$ are cloud point coordinate, $\rho$ is the slope distance between laser scanner instrument and object, $\theta$ is the horizontal angle and $\alpha$ is the vertical angel. Back sighting a target cannot be carried out by using (TLS). It
scans all the objects in his field of view. In data processing step, coordinates of the registration targets is known when using a special processing algorithms. Some of (TLSs) special targets (see figure 1) can be distributed in the field of view before scan process. These targets are neither retro-reflective nor made from special materials. Their 3-D coordinates extracted by some (TLS) data processing software, for example (Leica HDS Cyclone 5.1 and Z+F laser control v6.6.1.0), 3-D coordinates for plan targets could be also measured with a total station in a ground coordinate system before or after the scanning process for the registration purpose.

Accuracy of acquiring the coordinates of registration targets depends on the accuracy of the measurements (ρ, θ and α). The distance accuracy is influenced by several parameters. The main parameters are the surface properties (e.g. material, roughness, and color), the angle of incidence and the distance. The present atmosphere (temperature, air pressure) can also influence the distance accuracy. The accuracy of the final complete scan object will depends on the accuracy of the transformation parameters between all the scans. The accuracy of acquiring the coordinates of registration targets depends on the range between the scanner and the targets and also the distribution of these targets according to field of view of the scanner. Two types of special registration targets have been used in this work. First type is black-white and second type is polystyrene spheres, their surface cloud points were exported and the center coordinates are fitted by using least squares solution.

Estimation of transformation parameters could be solved either by using the combined or parametric least squares adjustment procedure. In this paper, the combined model is utilized based on assuming set of targets coordinates in adjacent two reference systems are observations. A stochastic assessment procedure has been developed to take into account the range between the scanner and the registration targets in the left and right scan. Results of transformation parameters from the used registration targets have been compared. Different stochastic models were employed with the least squares solution.

REGISTRATION MODEL

The registration of each scan world in any project is reduced to the computation of a 3D conformal transformation. The least squares registration algorithm has been used to calculate the registration parameters. Assuming that two scans and the coordinates of the registration targets in two adjacent scans are available, it is required to transform one of the two scans concerned (e.g. the right one) into the inner reference system of the first scan (e.g. the left one) as shown in figure (1). Assume we have the coordinates in the two systems as following:

\[ X_l = [\cdots, X_{lZ}, Y_{lZ}, Z_{lZ}, \cdots]^T \text{ and } x_r = [\cdots, x_{rZ}, y_{rZ}, z_{rZ}, \cdots]^T \]

where \( X_l \) coordinate vector for identical tie targets from left scan and \( x_r \) coordinate vector for identical tie targets from right scan. Scale factor is not assumed between the adjacent scans, assuming the laser scanner instrument is calibrated before taking the measurements. The relation between the two coordinate systems using six transformation parameters will be as following.

\[
\begin{bmatrix}
X_l \\
Y_l \\
Z_l \\
\end{bmatrix} =
\begin{bmatrix}
T_x \\
T_y \\
T_z \\
\end{bmatrix} +
\begin{bmatrix}
r_{11} & r_{21} & r_{31} \\
r_{12} & r_{22} & r_{32} \\
r_{13} & r_{23} & r_{33} \\
\end{bmatrix}
\begin{bmatrix}
x_r \\
y_r \\
z_r \\
\end{bmatrix}
\]

where: \( T_x, T_y, T_z \) are translations of the origin in the x, y, z directions and \( r \) is the rotation matrix. The definitions of the elements of the rotation matrix \( r \) is given as following.
where $\alpha$, $\phi$, and $\kappa$ are rotations about the x, y, z axes respectively.

\[
\begin{align*}
    r_{11} &= \cos \phi \cos \kappa \\
    r_{12} &= \cos \alpha \sin \kappa + \sin \alpha \sin \phi \sin \kappa \\
    r_{13} &= \sin \alpha \sin \kappa - \cos \alpha \sin \phi \cos \kappa \\
    r_{21} &= -\cos \phi \sin \kappa \\
    r_{22} &= \cos \alpha \cos \kappa - \sin \alpha \sin \phi \sin \kappa \\
    r_{23} &= \sin \alpha \cos \kappa - \cos \alpha \sin \phi \sin \kappa \\
    r_{31} &= \sin \phi \\
    r_{32} &= \sin \alpha \cos \phi \\
    r_{33} &= \cos \alpha \cos \phi
\end{align*}
\]

Transformation of coordinates can be either linear or non-linear. In linear solution case, the unknown’s number will be twelve (nine from rotation elements matrix and three translation) after neglecting the influence of the scale factor between the adjacent scans. Therefore the number of registration targets to be measured for every adjacent scan should be four, but a higher number is strongly recommended to increase the numerical stability and reliability of the solution. For non-linear solution, coordinates of minimum three target points in every adjacent scans is required to compute the registration parameters or the orientation to the object system but an approximation values for the parameters are very important. Considering only two scans to register, the observations will be the coordinates of the target points from the two scans. For every registration target three equations are required in the mathematical model as follow:

\[
\begin{align*}
    f_1 &= T_x \cdot (r_{11} \cdot x_r + r_{21} \cdot y_r + r_{31} \cdot z_r) - X_L \\
    f_2 &= T_y \cdot (r_{21} \cdot x_r + r_{22} \cdot y_r + r_{23} \cdot z_r) - Y_L \\
    f_3 &= T_z \cdot (r_{31} \cdot x_r + r_{23} \cdot y_r + r_{33} \cdot z_r) - Z_L
\end{align*}
\]
This model can be solved using the combined least squares adjustment model, which has the following mathematical model:

\[ f(\hat{l}, \hat{x}) = 0 \]  

(6)

where \( \hat{l} \) is the vector of adjusted observations, \( \hat{x} \) is the vector of adjusted transformation parameters. With the combined least squares adjustment solution the stochastic model or the variance-covariance matrix will take the form:

\[ C_{ll} = \sigma_{\hat{l}}^2 Q_{ll} \begin{bmatrix} \sigma_{\hat{x}r}^2 & 0 \\ 0 & \sigma_{\hat{x}l}^2 \end{bmatrix} \]  

(7)

where \( \sigma_{\hat{x}r}^2 \) and \( \sigma_{\hat{x}l}^2 \) are covariance matrix of observations and indicates that all covariances are zero. The weight matrix of the observations will take the following form

\[ P = Q_{ll}^{-1} = \begin{bmatrix} Q_{\hat{x}r}^{-1} & 0 \\ 0 & Q_{\hat{x}l}^{-1} \end{bmatrix} \]  

(8)

Assuming that the set of coordinates in the first scan world are error less (fixed), also equation (2) could be solved by using the parametric least squares adjustment model which take the following form:

\[ \hat{l} = f(\hat{x}) \]  

(9)

The stochastic model or the variance-covariance matrix will consider only the observation from the right scan, also the weight matrix of the observations will take the following form:

\[ P = Q_{ll}^{-1} = \begin{bmatrix} Q_{\hat{x}r}^{-1} \end{bmatrix} \]  

(10)

Details of combined least squares solution can be found elsewhere (Niemeier, 2002).

**Approximate Transformation Parameters**

Linearization of the equations need six approximate values for the six unknown parameters (three rotations angels and translation vector) of each model to the global reference system, because the equations of the transformation are not linear, and a least squares iterative solution is applied. Many algorithms can be found in literature, to overcome this difficulty, e.g. based on quaternion (Sanso, F, 1973), orthogonal procrustes analysis (Beinat et al., 2001) and vector algebra (Dewitt, 1996).

In this work the approximation parameters have been calculated using the concept of (Dewitt, 1996) the rotation angles are determined in seven steps:
1. Select the three geometrically strongest points which widely distributed base. A formula for the square of the altitude is given by the equation

\[ h^2 = b^2 - \left( \frac{a^2 + b^2 - c^2}{2 \cdot a} \right) \]  

(11)

where \( h \) is altitude for every three points, \( a, b \) and \( c \) are the lengths of the triangle see figure 3.

2. Compute the normal vectors at the strongest points in the two scans.
3. Determine tilt and azimuth for the normal in each scan from equations 12 and 13.

\[
tilt = \tan^{-1} \left( \frac{k}{\sqrt{i^2 + j^2}} \right) + 90^\circ
\]

(12)

\[
azimuth = \tan^{-1} \left( \frac{i}{j} \right)
\]

(13)

4. Perform an initial rotation of points in the two scans using corresponding values of tilt and azimuth.
5. Determine swing by difference in azimuths for the common line.
6. Combine the two tilts, two azimuths, and one swing into one overall rotation matrix.
7. Form rotation matrix and compute values for \( \dot{\alpha} \), \( \phi \) and \( \kappa \).

Transformation equation is linear in terms of translation vector initial values are not required. However, it could be calculated by rearrange the equation 2 and calculate all the values of translation vector.
TEST FIELD

In order to test the registration algorithm and get the results, laser system IMAGER 5003 from the Zoller+Froehlich company has been used to scan the cross section Wenden (about 15 kilometer away from Braunschweig city center). The scanned area is approximately 50m (W) x 40m (L).

Table 1. Imager 5003 System Specifications.

<table>
<thead>
<tr>
<th>Measurement technique</th>
<th>phase shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Field of View:</td>
<td>310°</td>
</tr>
<tr>
<td>Horizontal Field of View:</td>
<td>360°</td>
</tr>
<tr>
<td>Vertical Resolution:</td>
<td>0.018°</td>
</tr>
<tr>
<td>Horizontal Resolution:</td>
<td>0.009°</td>
</tr>
<tr>
<td>Vertical Accuracy:</td>
<td>0.02° rms</td>
</tr>
<tr>
<td>Horizontal Accuracy:</td>
<td>0.02° rms</td>
</tr>
<tr>
<td>Max. vertical scanning speed:</td>
<td>2,000 rpm</td>
</tr>
<tr>
<td>Max. number of pixels vertical:</td>
<td>15,000</td>
</tr>
<tr>
<td>Max. number of pixels horizontal:</td>
<td>18,000</td>
</tr>
<tr>
<td>Scanning time (8,000 x 8,000 pixel image, total field of view):</td>
<td>140 sec.</td>
</tr>
</tbody>
</table>

Figure 4. The laser system IMAGER 5003.

Figure 5. Cross section Wenden, distribution of sphere targets and two scan positions.

Figure 4 and table 1 describe the scanner system and the technical specifications. For the registration purpose, 10 black-white plane square targets printed with size DIN A4 have been placed and also uncelebrated 4 polystyrene
spheres with special holder. Figure 5 describes the two positions of the scan and the distribution of the 4 sphere registration targets. For the two scan positions, two ASCII files from the software Z+F Laser control have been registered, one file per scan; *.zfs file with sizes: 160 and 157MB. Figure 6 shows the two scans exported from the software Z+F Laser control with an intensity image.

![Figure 6. Intensity images of the scans.](image)

**Extracting Coordinates of Registration Targets**

The scanning program Z+F Laser control has a special icon to find only the black-white targets. To do this, the user should manually find and adjust the mouse as close as possible to the cross which separate the black-white in the target. All measured targets have been labeled and their coordinates exported into the ASCII files 4 columns point number x, y, z. This operation should be done in every scan. Table 1 shows the transformation parameters and fitting quality by using the best 5 black-white targets illustrated. Also, the transformation parameters from some available software’s are compared, these software’s are Leica Geosystems HDS Cyclone 5.1 is 3D point cloud processing software for laser scanner observation. Australis is a software system for automated off-line digital close range photogrammetric image measurement, orientation triangulation and sensor calibration. Panda is a program for the adjustment of the networks and deformation analysis wich recently developed for handling 1D-, 2D- and 3D-networks in engineering surveying (Niemeier et al., 1990). Table 2 shows the results of the registration using our model and its fitting quality as well as the result from Cyclone, Australis and Panda software.

We noticed that no quality fitting to describe the goodness of the parameters when using Cyclone software, the differences in the rotation angels \( \omega \), \( \varphi \) and \( \kappa \) were 0°06'57'', 0°09'55'' and 0°00'08'', respectively, also the differences in translation vector \( T_x, T_y \) and \( T_z \) were 18.4, 6.8 and 3.0 mm, respectively. The following section will cover the calculation or modeling the center of a sphere to use it as a tie points between the adjacent scans for the current study.

**Fitting a Sphere to Point Clouds for Data Registration**

The two scans data were imported from *.*zfs data to *.*imp data by using Cyclone 5.1. With this program it is possible to work with 3D windows to select and export the cloud points for every sphere into ASCII files 4 columns (x, y, z, intensity). Spheres scanned from different positions in different scans are used as three-dimensional targets. The main advantage of the spherical targets is their viewing from any laser standpoint. In our tests, 4 polystyrene spheres with nun calibrated radius about 15 cm.
Table 2. Transformation parameters and fitting quality by using black-white targets

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Our solution</th>
<th>Cyclone</th>
<th>Australis&amp;Panda</th>
<th>Fitting quality of the parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>ω</td>
<td>-0°26'24&quot;</td>
<td>-0°33'21&quot;</td>
<td>-0°26'24&quot;</td>
<td>359&quot; na * 321&quot;</td>
</tr>
<tr>
<td>φ</td>
<td>0°1'26&quot;</td>
<td>-0°11'21&quot;</td>
<td>0°1'26&quot;</td>
<td>177&quot; na 158&quot;</td>
</tr>
<tr>
<td>κ</td>
<td>-44°02'39&quot;</td>
<td>-44°02'47&quot;</td>
<td>44°02'39&quot;</td>
<td>159&quot; na 142&quot;</td>
</tr>
<tr>
<td>$T_x$</td>
<td>14.4597 m</td>
<td>14.4413 m</td>
<td>14.4597 m</td>
<td>13.9 mm na 16. mm</td>
</tr>
<tr>
<td>$T_y$</td>
<td>-7.5088 m</td>
<td>-7.5156 m</td>
<td>-7.5088 m</td>
<td>17.5 mm na 16.1 mm</td>
</tr>
<tr>
<td>$T_z$</td>
<td>0.080 m</td>
<td>0.0797 m</td>
<td>0.080 m</td>
<td>20.7 mm na 18.5 mm</td>
</tr>
</tbody>
</table>

To be able to use the spheres, the parameterisation should not depend on the sphere whether it is partly occluded or not. A sphere can be described as follows:

The radius ($r$)

The centre co-ordinates ($x_c, y_c, z_c$)

Finding the parameters of a sphere is an iterative process, therefore, initial values have to be determined beforehand. The radius and the centre of the sphere can be solved from the following equation:

$$0 = (x_i - x_c)^2 + (y_i - y_c)^2 + (z_i - z_c)^2 - r^2$$ (14)

Where: $x_c, y_c, z_c$ Center coordinate, $x_i, y_i, z_i$ Surface coordinates for the spheres from laser scanner. This method is based on minimizing the mean square distance from the sphere to the data points. Since this is a non-linear problem, initial values are needed for the parameters of the sphere.

$$r = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2 + (z_i - z_c)^2}$$ (15)

Approximate values for the parameters are provided by (Eberly, D.1999) algorithm. The proposed algorithm has been implemented in C++ program, in order to calculate the parameters of sphere. The following two figures describe the relation between the distance from the scanner and the centre coordinates accuracy.

Figure 7 represents the relation between the accuracy of centre coordinates of modelled 4 spheres from two scans. The results show good relation between the range from the scanner and the accuracy of sphere parameters.

* na means not available by the software
Figure 7. Accuracy of centre coordinates of modelled spheres according to the range from Laser scanner.

Stochastic Assessment for Target Coordinates

Laser scanner observations are contaminated by several kinds of errors and biases, namely, the surface properties (e.g. material, roughness and color), the angle of incidence and the distance between the scanner and the target. Also for long range applications the present atmosphere (temperature and air pressure) influences the distance accuracy. Due to the complex nature of these errors, rigorous modelling, in general, cannot be achieved. The remaining error components must be modelled stochastically through the least square stochastic model (the observation covariance matrix). The variances (diagonal elements of the covariance matrix) describe their statistical quality while the covariance (off-diagonal elements) describes their correlation between the observations. The relative accuracy 3D coordinates of tie points which used in data registration is accounted by weighting the more precise one higher than the less one. Equation 16 shows a model of the relative weight matrix for one tie point which has 3D coordinates from two adjacent scan.

\[
P = \begin{bmatrix}
\frac{1}{\rho_i} & 0 & 0 \\
0 & \frac{1}{\rho_i} & 0 \\
0 & 0 & \frac{1}{\rho_i} \\
\end{bmatrix}
\]  

\[= \begin{bmatrix}
\frac{1}{\rho_i} & 0 & 0 \\
0 & \frac{1}{\rho_j} & 0 \\
0 & 0 & \frac{1}{\rho_j} \\
\end{bmatrix}
\]

(16)

where \( \rho_i \) is the range between the scanner and registration target in right scan and \( \rho_j \) the range between the scanner and the same registration target in left scan. According to the assumption that the variance of center coordinates of the sphere tie target is proportional to the range between the sphere center and the scanner, three candidates or models from the relative weight matrix were used with the least square solution to calculate transformation parameters and their impact on the quality of the unknowns that were analysed:

An identity weight matrix (Equal weights) \( P = I \).

The range between the scanner and the target dependent (i.e. \( \sigma_{\text{range}}^2 = \sigma_{x_i}^2 = \sigma_{y_i}^2 = \sigma_{z_i}^2 \propto \text{range}^2 \)).

The range square between the scanner and the target dependent (i.e. \( \sigma_{\text{range}}^2 = \sigma_{x_i}^2 = \sigma_{y_i}^2 = \sigma_{z_i}^2 \propto \text{range}^2 \)).
With the last two relative weight models, the influence of the less precise tie point is reduced and the more precise is increased that means better results for the data registration is expected.

Table 3. Transformation parameters and their fitting quality by using spheres targets.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Equal weights</th>
<th>Weighted 1/\text{range}</th>
<th>Weighted 1/\text{range}^2</th>
<th>Equal weights</th>
<th>Weighted 1/\text{range}</th>
<th>Weighted 1/\text{range}^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\omega)</td>
<td>-0°26'04''</td>
<td>-0°26'04''</td>
<td>-0°26'04''</td>
<td>253''</td>
<td>207''</td>
<td>186''</td>
</tr>
<tr>
<td>(\phi)</td>
<td>-00°00'45''</td>
<td>-00°00'46''</td>
<td>-00°00'46''</td>
<td>139''</td>
<td>130''</td>
<td>126''</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>-44°04'57''</td>
<td>-44°04'54''</td>
<td>-44°04'47''</td>
<td>122''</td>
<td>109''</td>
<td>103''</td>
</tr>
<tr>
<td>(T_x)</td>
<td>14.4383 m</td>
<td>14.4411 m</td>
<td>14.4423 m</td>
<td>9.1 mm</td>
<td>7.7 mm</td>
<td>7.0 mm</td>
</tr>
<tr>
<td>(T_y)</td>
<td>-7.5236 m</td>
<td>-7.5236 m</td>
<td>-7.5233 m</td>
<td>10.7 mm</td>
<td>9.5 mm</td>
<td>8.8 mm</td>
</tr>
<tr>
<td>(T_z)</td>
<td>0.0955 m</td>
<td>0.0955 m</td>
<td>0.0955 m</td>
<td>12.0 mm</td>
<td>10.4 mm</td>
<td>9.8 mm</td>
</tr>
</tbody>
</table>

Table 3 shows the transformation parameters and their fitting quality by using three different relative weight matrix models. The range square dependant model gave the best results.

CONCLUDING REMARKS

In this paper, a background about the algorithms and some techniques for data registration has been presented. The combined least squares as a method for data registration has been used to calculate the transformation parameters. It maximizes the accuracy of the complete 3D scan model by allowing each individual coordinate of registration targets in both global and local systems to be weighted. A real test has been carried out in order to evaluate the registration parameters and their fitting quality by using two types from special registration targets (black-white and polystyrene sphere targets). By using the software Z+F Laser control, it is possible to extract manually the 3D information for the black-white targets. Algorithms for fitting a sphere to point clouds to be used for data registration were also presented. Test results with real data have been done, results from our solution and some laser scanner data processing software such as, Cyclone 5.1, Australis and Panda, were compared.

According to the registration targets type, the sphere targets gave the best results. The accuracy of extracting sphere parameters is range dependent. By using range with the relative weight matrix which used in combined model to calculate transformation parameters between adjacent scan the results are improved.

REFERENCES

Cyclone user’s manual, December 2002.