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DEFORMATION ANALYSIS WITH 3D LASER SCANNING

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Abstract: In the paper a technology is described which uses terrestrial laser scanning for the observation of deformation objects. Not points but planes and their position changes are observed. Targets are neither necessary for the transformation of scanner stations nor for the deformation analysis itself. The scanner stations can be chosen arbitrary and they have not to be identical between the epochs.

1. INTRODUCTION

Proving and modeling of deformation processes are one of the main tasks of engineering surveying. At the currently used deformation models the relevant object is discretized by points. The positions of these points are determined at definite times. Possibly existing deformation processes can be concluded from position changes.

Prerequisite for this procedure is the existence of object points which can be sighted. If such points are not available they have to be created with targets.

Furthermore it has to be known where deformations can appear before measuring the zero epoch. If deformations appear in regions which where not observed these deformations are not detectable.

3D laser scanning technology gives now the opportunity to record an object as a whole. It has no longer to be known a priori where deformations have to be expected. Deformations can be detected where they appear.

But in contrast to the classical technology no discrete identical points are available anymore. This problem can be solved if parts of the point cloud are grouped and the points in these groups are seen as representatives of a parametrizable surface. An example for such a proceeding is the use of target spheres for the registration of scans. The radius of the spheres is known and the centre point coordinates can be calculated by a best fit algorithm. These coordinates then can be introduced in a classical transformation calculation using identical points.

But such an approach has crucial disadvantages. First it is necessary to use artificial targets and it can be of high effort to place these targets. Secondly only a very small part of the redundancy contained in overlapping scans is used for the calculation. The resulting accuracy of the orientation parameters is therefore often not sufficient for detecting deformations.

The technology described in this paper uses already available surfaces (in a first step only planes) of the scanned objects itself. Artificial targets are not necessary anymore. A wide part of the existing redundancy is used and the achieved accuracy is adequate for deformation analysis.

The analyzation procedure is structured in the steps: Plane detection, matching, interconnected transformation of the scanner station inside the single epochs and epoch comparison (test for congruence). The plane detection happens automatically, separately for each individual scan. The process is controlled by stochastic parameters which are derived from the accuracy of the scanner and which determine the degree of abstraction of the plane detection. Dependent on the project conditions the matching is performed in a fully or semi automatic way. Result of the matching process is information about topological identities between planes from different scans. The individual scans are transformed in a unique datum by an interconnected transformation using identical planes. The epoch comparison again uses the same approaches of matching and interconnected transformation.

2. PLANE DETECTION

The detection of planes happens separately for each scan in the corresponding image matrix. Rows and columns of the image matrix represent the discretized vertical respectively horizontal angles of the points in the coordinate system of the scanner. Within an iterative process the image matrix is split into sub matrices. After each iteration step an adjusted plane is calculated approximating the points contained in the resulting sub matrices. The iteration process continues as long as a sub matrix stays planar or the stop criterion is reached.

Figure 1- Point cloud of a church ruin

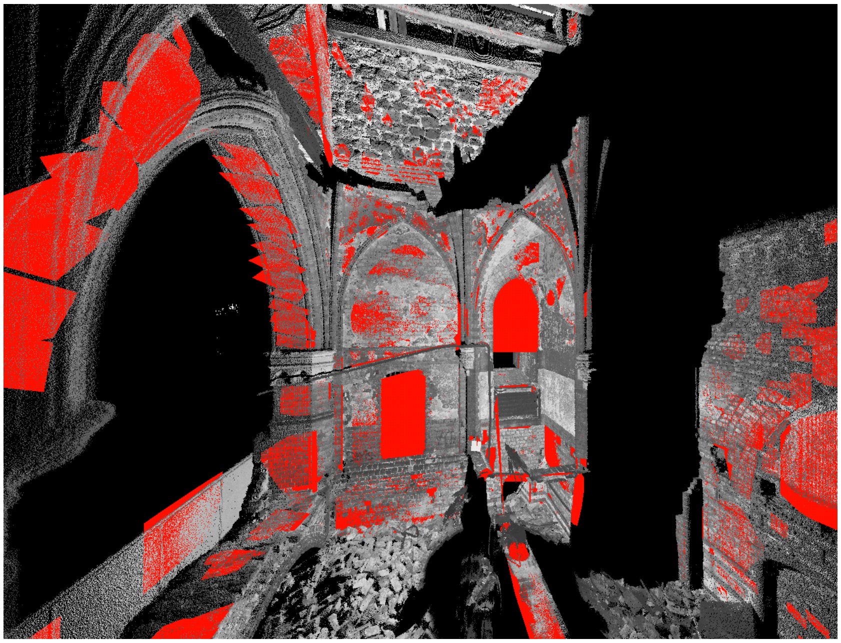

Figure 2 - Point cloud of a church ruin with detected planes (in red)

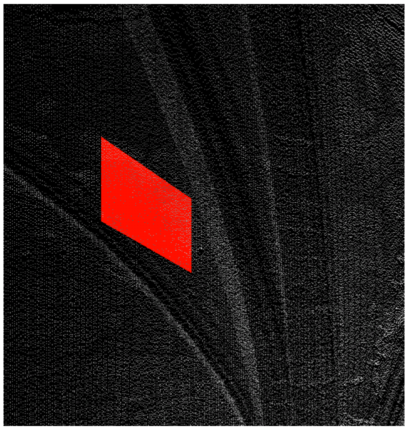

Figure 3 - Detail of a point cloud with a single detected plane

Figures 1-3 show the result of a plane detection process in the scan of a church ruin. The resulting parameters for each plane are the normal vector, the covariance matrix of the normal vector components and the coordinate centroid.

There are two criteria which have to be fulfilled for accepting a group of points to be planar, both resulting of the plane adjustment. The first criterion is the estimated standard deviation of a single point and decides if the point group is planar. The second criterion is the estimated standard deviation of the top of the normal vector. This value is used as decision criterion if the adjusted plane can be seen as significant or not.

3. MATCHING

The objective of the matching process is to find identical planes in different scans. Result is pure topological information containing pairs of identical planes. The algorithm works on a pair of two scans on a time. There are two variants of matching: the datum independent and the datum dependent matching.

3.1 Datum Independent Matching

The datum independent matching needs no advance information about orientation or translation of the two scans in process, with the exception that both scanner axes were assumed to be approximately vertical during the scanning process.

Prerequisites for the functioning of this kind of matching are an adequate overlapping range and a not too regular arrangement of the scanned objects.

The matching happens separately for the rotation and translation. For rotatory matching correlations of the normal vectors are used. In an iterative process candidates for identical normal vectors are found. In a subsequent adjustment outliers showing up due to the found identities are removed.

On the basis of the found rotation parameters the translation matching follows using the translation parameters of the local planes.

Last step of the matching process is a strict adjustment calculation considering rotation and translation parameters (see point 4). During this adjustment all mismatches are iteratively removed.

3.2 Datum Dependent Matching

If the overlapping range between two scans is too small or the scanned objects are arranged in a regular order, e.g. rectangular or with regular distances, then the datum independent matching doesn't work and it becomes necessary to use the datum dependent matching algorithm.

This algorithm works on the basis of global plane parameters. Therefore both scans under consideration have to be approximately transformed into a common datum before the matching can be performed. For that purpose one scan is used as a fix reference station while the other scan is regarded as a new station. For the classical 3D transformation at least three pairs of approximately identical points are used. With the resulting transformation parameters all plane parameters and the corresponding covariance matrices of scan two are transformed in the datum of scan one.

The search of candidates of identical planes is supported by a 4D search tree. The four dimensions are the components of the global normal vectors and the global translation parameters. Each detected candidate is then tested by a χ^2-Test for significant differences in the plane parameters.

Analogous to the datum independent matching the last step is a strict adjustment in which coarse mismatches are iteratively removed.

4. INTERCONNECTED TRANSFORMATION

Due to the interconnected transformation an arbitrary number of scans can be transformed into a common datum with an adjustment calculation of one piece. The process is subdivided into the three steps interconnected rotation, interconnected translation and strict adjustment. All steps use the Gauss-Helmert-Model as adjustment approach and the same adjustment kernel for the calculation. To be able to differentiate the partly very complex equations automatic differentiation algorithms were used.

4.1 Interconnected Rotation

The interconnected rotation provides the proximity rotation parameters for the strict adjustment. The calculation is modelled in 2D what assumes that the scanner axes were approximately vertical during the scan process. Observations are the x- and y-components of the local normal vectors. Unknowns are the elements of the rotation matrix of each station.

Each plane identity provides two condition equations:

$$\mathbf{R}_k \cdot \mathbf{n}_i - \mathbf{R}_l \cdot \mathbf{n}_j = 0 \quad \text{with} \quad \mathbf{R} = \begin{pmatrix} a & -o \\ o & a \end{pmatrix} \quad \text{and} \quad \mathbf{n} = \begin{pmatrix} n_x \\ n_y \end{pmatrix} \tag{1}$$

For the new stations the determinant of the rotation matrix has to be 1. This leads to one restriction:

$$a_k^2 + o_k^2 = 1 \tag{2}$$

The elements of the rotation matrices of the reference stations are directly determined by two restriction equations:

$$\begin{aligned} a_k &= \text{const.} \\ o_k &= \text{const.} \end{aligned} \tag{3}$$

Because all equations are linear or bilinear and due to the lack of singularities it is possible to solve this adjustment problem without proximity values. The iteration process always converges.

4.2 Interconnected Translation

The interconnected rotation provides the proximity translation parameters for the strict adjustment. It uses the coordinates of the local plane centroids $\mathbf{s}_i$ as observations. Unknowns are the coordinates of the individual scanner stations $\mathbf{t}_k$. All centroid coordinates are introduced with a uniform standard deviation of 0.1m what is adequate for the calculation of proximity values. The rotation parameters of the stations calculated in the former step are now regarded as constants. Both, rotation and translation are expressed as quaternions.

$$\begin{aligned} &\text{rotation} && \dot{q}_k = \dot{q}_k\left(q_0, \quad q_x, \quad q_y, \quad q_z\right) \quad \text{with} \quad q_0^2 + q_x^2 + q_y^2 + q_z^2 = 1 \\ &\text{translation} && \dot{t}_k = \dot{t}_k\left(0, \quad t_x, \quad t_y, \quad t_z\right) \end{aligned} \tag{4}$$

Each plane identity then gives three condition equations:

$$\dot{t}_k + \dot{q}_k \cdot \dot{s}_i \cdot \dot{q}_k^{-1} - \dot{t}_l - \dot{q}_l \cdot \dot{s}_j \cdot \dot{q}_l^{-1} = 0 \tag{5}$$

The translation components of the reference stations are directly determined by three restriction equations:

$$\begin{aligned} t_x &= \text{const}. \\ t_y &= \text{const}. \\ t_z &= \text{const}. \end{aligned} \tag{7}$$

Because all equations are linear it is possible to solve this adjustment problem without proximity values in one step.

4.3 Strict Adjustment

The observations introduced in the strict adjustment are the local normal vectors $\mathbf{n}_i$ and the local coordinate centroids $\mathbf{s}_i$ of the planes. The stochastical model is given by the covariance matrices of the local plane parameters resulting from the former plane fitting. Unknowns are the rotation quaternions q_k and the translation vectors $\mathbf{t}_k$ of the scanner stations. All equations are formulated in quaternion notation.

Each plane identity gives three condition equations for the rotation

$$\underbrace{\dot{q}_k \cdot \dot{n}_i \cdot \dot{q}_k^{-1}}_{\dot{n}_{i\,\text{global}}} - \underbrace{\dot{q}_l \cdot \dot{n}_j \cdot \dot{q}_l^{-1}}_{\dot{n}_{j\,\text{global}}} = 0 \tag{8}$$

and one condition equation for the translation.

$$\underbrace{\left(\dot{q}_k \dot{n}_i \dot{q}_k^{-1}\right)}_{\dot{n}_{i\,\text{global}}} \cdot \underbrace{\left(\dot{t}_k + \dot{q}_k \dot{s}_i \dot{q}_k^{-1}\right)}_{\dot{s}_{i\,\text{global}}} - \underbrace{\left(\dot{q}_l \dot{n}_j \dot{q}_l^{-1}\right)}_{\dot{n}_{j\,\text{global}}} \cdot \underbrace{\left(\dot{t}_l + \dot{q}_l \dot{s}_j \dot{q}_l^{-1}\right)}_{\dot{s}_{j\,\text{global}}} = 0 \tag{9}$$

These four equations formulate the constraint that the global plane parameters of two planes have to be identical.

For the new stations the rotation quaternions have to be normalized what leads to one restriction equation for each new station:

$$\left|\dot{q}_k\right| \overset{!}{=} 1 \quad \Rightarrow \quad q_0^2 + q_x^2 + q_y^2 + q_z^2 = 1 \tag{10}$$

4.4 Datum Determination

Currently there are two options to determine the datum. The first is to fix the transformation parameter of one or more reference stations with seven restriction equations per reference station:

$$\begin{aligned} &\text{rotation:} && q_0 = \text{const.},\quad q_x = \text{const.},\quad q_y = \text{const.},\quad q_z = \text{const.}, \\ &\text{translation:} && t_x = \text{const.},\quad t_y = \text{const.},\quad t_z = \text{const.} \end{aligned} \tag{11}$$

The second option is a free adjustment. This leads to three restriction equations for the rotation and three for the translation. The translation equations are simple:

$$\sum_i t_{xi} = \sum_i t_{xi}^0, \qquad \sum_i t_{yi} = \sum_i t_{yi}^0, \qquad \sum_i t_{zi} = \sum_i t_{zi}^0 \tag{12}$$

The rotation equations minimizes the differences of the components between a unit vector rotated with the proximity quaternion and the same vector rotated with the adjusted quaternion:

$$\begin{aligned}\sum_i 2\left(q_{0i}q_{xi} + q_{yi}q_{zi}\right) &= \sum_i 2\left(q_{0i}^0 q_{xi}^0 + q_{yi}^0 q_{zi}^0\right)\\ \sum_i 2\left(q_{xi}q_{zi} - q_{0i}q_{yi}\right) &= \sum_i 2\left(q_{xi}^0 q_{zi}^0 - q_{0i}^0 q_{yi}^0\right)\\ \sum_i 2\left(q_{xi}q_{yi} + q_{0i}q_{zi}\right) &= \sum_i 2\left(q_{xi}^0 q_{yi}^0 + q_{0i}^0 q_{zi}^0\right)\end{aligned} \tag{13}$$

In the case of a free adjustment it is furthermore necessary to normalize the quaternions of all stations.

4.5 Adjustment Results and Interpretation

Results of the adjustment calculation are the transformation parameters for each scanner station and their covariance matrix. The empirical standard deviations of the translation parameters are easy to interpret. The empirical standard deviation of the orientation angle σ_φ can be calculated from the variance of q_0.

$$q_0 = \cos\frac{\varphi}{2} \quad \Rightarrow \quad \sigma_\varphi = \frac{2}{\sqrt{1-q_0^2}} \cdot \sigma_{q_0} \quad \text{for} \quad q_0 \neq 1 \tag{14}$$

Each plane identity can be tested if the discrepancies in the global plane parameters of the belonging planes are significant. Test value is the quadratic form

$$\chi^2 = \mathbf{d}^T \mathbf{C}_{dd} \mathbf{d} \quad \text{with} \quad \mathbf{d} = \begin{pmatrix} n_{xi} - n_{xj} \\ n_{yi} - n_{yj} \\ n_{zi} - n_{zj} \\ d_i - d_j \end{pmatrix} \quad \text{and} \quad \mathbf{C}_{dd} = \mathbf{C}_{ii} + \mathbf{C}_{jj} \tag{15}$$

This test value is used for a stepwise detection and elimination of incorrect identities during the adjustment process.

5. EPOCH COMPARISON

In a classical deformation analysis process parameter vectors and its covariance matrices are given from former adjustment calculations separately for each epoch. These parameter vectors are pair wise associated in an adjustment. In an iterative process parameter identities which do not fit are eliminated until a consistent result is reached.

To be able to apply this strategy in connection with our type of data it would be necessary to calculate all global plane parameters and their corresponding covariance matrices. But this way seems not to be efficient because of the large number of automatically detected planes. Therefore the same observations are used and the same unknowns are calculated like for the two separate epoch adjustments. In the common adjustment calculation of two epochs not fitting across-epoch-identities are eliminated iterative till a consistent state is reached.

Results are the adjusted transformation parameters of the scan stations of two epochs. With these transformation parameters the global plane parameters of all planes in the participating epochs can be calculated. Planes from different epochs with a significant overlap in mutual projection but being not identical can be seen as deformation areas.

With the resulting transformation parameters all separate point clouds can be transformed into a common reference frame. If the points of different epochs have different colors then the generation of sections is a good option to visualize the detected deformations. Figure 4 shows the detail of a displaced pylon with a displacement of about 3cm.

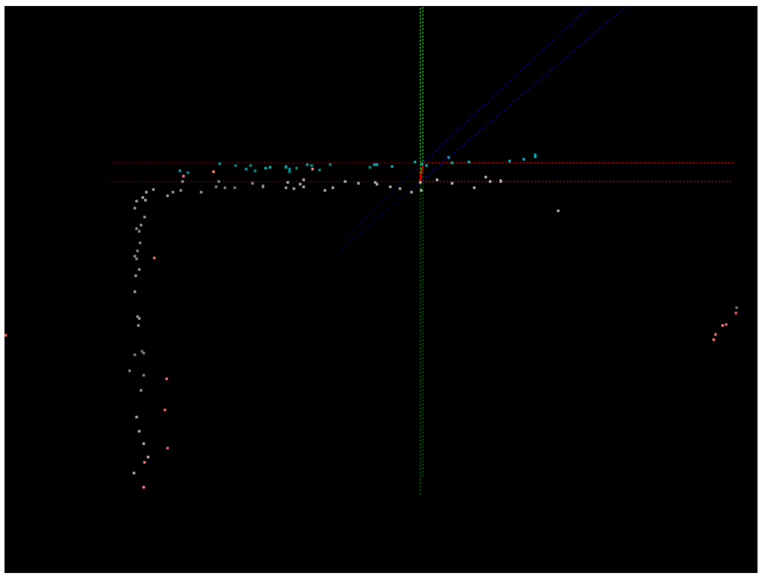

Figure 4 - Detail of a deformation area

6. FIRST EXPERIENCES

The mathematical model presented above was implemented in the software system SiRailScan of the company technet GmbH and was used for several projects. The scanner in use was an Imager 5003 from Zoller+Froehlich. In the most cases a monitoring of the reconstruction of cultural heritage buildings was requested. Typical for this kind of objects are irregular surfaces consisting of brigs, sandstone or plaster.

The scanner provides a standard deviation for a single measured distance of about 3mm. It turned out that a limit of 5mm for the empirical standard deviation for the point plane distance is feasible. This value takes in account the accuracy of the scanner and contains also a part for the abstraction of the surface. For the significance of the normal vector a limit value of 10mm were chosen. With these parameters the automated plane detection provided a number of between 100 and 800 planes per scan.

The automated datum independent matching worked in about 75% of the cases. In 25% a preliminary transformation over three points was necessary. The number of found plane identities was dependent on the size of the overlap range. This number was approximately in a range between 20 and 200.

In the interconnected transformation blocks of up to 20 individual scans were transformed into a unique reference frame. A larger number of scans is possible but wasn't necessary. The empirical standard deviation of the translation vector of two adjacent scans was between 0.8mm and 3mm.

The average residual of the translation parameter of the local planes was about 1mm. Deformations of >1cm could easily be detected.

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