DEFORMATION MONITORING BASED ON TERRESTRIAL LASER SCANNER POINT CLOUD REGISTRATION

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Abstract: Terrestrial laser scanning, although a recent technology is shown to be promising for deformation detection and monitoring applications. However, general practice for deformation monitoring with laser scanners requires use of predefined targets. A methodology for measuring structural deformation, based on the acquisition of terrestrial laser point clouds from a deforming object without the use of targets, has been developed and presented in this paper. Instead of targets, a number of stationary control points located in the surrounding area of the object are used. These points are identified automatically on photographic images taken during laser scanner data acquisition from a high resolution CCD camera mounted on the scanner device and are used for the automatic registration of the point clouds. The paper also describes the application of the above methodology in laboratory experiments on a model of an ancient temple under stress caused by controlled motion.

1. INTRODUCTION

Deformation monitoring of structures requires spatial measurement techniques that are reliable, accurate, low-cost and easy to implement. While a number of techniques possess these characteristics, many require the use of predefined targets which may be disadvantageous in some cases, especially when the structure is inaccessible to operators. Terrestrial laser scanning has shown to be a promising technique for deformation detection and monitoring. The main advantage is that it is a non-contact measuring technique that generates very efficiently three-dimensional point clouds. However, the general practice for deformation monitoring with laser scanners still requires use of targets. This is because for large and complex objects it is often necessary to acquire point clouds from various positions, thus requiring the transformation of all clouds into a common coordinate system (i.e. registration process). The use of targets enables the registration process for the estimation of the 6 transformation parameters in space of the common reference system.

The automatic registration of overlapping point clouds from terrestrial laser scanners without the use of targets is an area where much research is currently being undertaken. The proposed methods for automatic registration can be distinguished into three main categories. The first category of methods use corresponding objects measured in different scans to determine the transformation parameters. Briefly, geometric forms, such as planes or cylinders, are fitted in different laser scans and an operator assigns correspondences between the measured objects

(Remondino, 2004). The second category of methods involves the use of the complete original data sets where the recovery of correspondence between two clouds is performed through local search algorithms. The most common algorithm is the Iterative Closest Point (ICP) or Chen and Medioni's method which work well if good a priori alignment is provided. However, in the case of the registration of partially overlapping and unorganised point clouds without good initial alignment, these methods are not appropriate and methods based on geometric primitives and neighbourhood search are used. The change of geometric curvature and approximate normal vector of the surface formed by a point and its neighbourhood are used to determine the possible correspondence of point clouds (Bae and Lichti, 2004).

The third category of methods involves the use of external information, in the form of photographic images taken from a high resolution CCD camera mounted on the scanner device, for the registration of point clouds. The images are used either to extract approximate information regarding the ICP algorithm or to identify invariant features from different view points in the point clouds.

In light of these methods, a methodology for measuring structural deformation, based on the acquisition of two or more terrestrial laser point clouds from a deforming object without the use of targets but with the use of external images, has been developed and is presented in this paper. At different data collection epochs, the position and orientation of the acquired scans are not the same. Therefore, the two point clouds should be transformed to a global reference system to enable comparison and hence extraction of deformation information. For this purpose, a number of stationary control points located in the surrounding area of the object are used. These points are identified automatically on photographs taken during laser scanner data acquisition from a high resolution CCD camera mounted on the scanner device. The position and orientation of the camera relative to the reference system of the laser scanner are estimated through appropriate calibration in a high accuracy control field. Since there is no one-to-one correspondence between the pixels of the photograph and the relevant point cloud, the position of a pixel on the object surface is estimated by interpolation. In this way, pixel coordinates are related to object X,Y,Z coordinates and control points identified on the photographs can be transformed to object points on the relevant point clouds. Using these control points, the parameters of a rigid body transformation relating both point clouds can be estimated. The comparison of the two point clouds is then possible by transforming the second point cloud to the reference system of the first point cloud. Section 2 of the paper presents the proposed methodology, with an emphasis on the essential steps for its implementation. Section 3 describes the application of the above methodology in laboratory experiments for the monitoring of deformations of cultural heritage structures under stress caused by controlled motion. The laboratory experiments have been performed on a model of an ancient temple which undergoes controlled stress by an earthquake table and results of these experiments are given. Finally, section 4 summarises the work and provides conclusions.

2. METHODOLOGY

The aim of the proposed methodology is the investigation of the deformation of an object in two or more discrete epochs. To simplify the description of the proposed method it is assumed that the entire object is captured in one scan acquisition and scanner position and orientation is changed between scans. It is also important to assume that the surrounding environment is considered as "stable" and a significant amount of this stable information is captured in each scan. In order to evaluate object positions at each epoch, all the acquired point clouds should be referenced in the same coordinate system. This will be accomplished by registering all the subsequent point clouds to the coordinate system of the first scan.

Registration involves the identification of sufficient number of control points as well as the estimation of the parameters of the transformation that connects two point clouds to each other. Assuming that there are variations in texture on the scanned areas, candidate control points can be automatically identified on the overlapping area of the two photographs which has been acquired together with the point clouds. The object coordinates of these points in the point cloud reference system can be calculated from their image coordinates. For this purpose, the interior orientation of the camera unit and its eccentricity to the laser scanning system should be known (Forkuo and King, 2004). The estimation of these parameters is achieved through a proper calibration procedure.

The coordinate transformation between two point clouds can be considered as a rigid body transformation, decomposed into a rotation and a translation. In the general case the scale may not be known, thus seven unknown parameters have to be estimated. Three control points with known coordinates in both systems are more than enough to permit the determination of the seven unknowns. In case of more than three control points a least squares adjustment solution should be employed (Horn, 1987).

2.1. System calibration

The majority of commercial laser scanner systems provide images of the scanned area along with the point cloud. However, these images may be of low resolution and not adequate for control point identification. To present a more accurate solution an external CCD camera is mounted on top of the scanner body. The CCD camera as a metric device has its own coordinate reference system which is different from that of the laser scanner. The aim of the system calibration is to determine the parameters of a transformation that connects the two coordinate systems.

Photogrammetry provides a variety of methods for determining the position and orientation of a camera in a scene and relates image measurements to scene coordinates. These issues are usually referred to as camera calibration problems. In the case of a non-metric camera, the camera calibration problem involves determining two sets of parameters: the extrinsic parameters, which are related to the transformation of a point to the camera coordinate system, and the intrinsic parameters which are related to the projection of the point onto the image plane.

The extrinsic parameters are station dependant and are usually referred to as exterior orientation. These are the three coordinates (X_0, Y_0, Z_0) of the perspective centre of the camera lens and the three rotation angles $(\omega, \varphi, \kappa)$ of the lens axes. The intrinsic parameters describe the internal geometry of the CCD camera and are usually referred to as interior orientation. The interior orientation is adequately represented by 10 parameters which are irrelevant to the camera station. These comprise the camera constant c for the distance of the image plane from the centre of the projection, the principal point for the origin of the image plane coordinate system, the lens distortion coefficients for correcting optical imperfections and the scale factors for rectangular pixel shape (Beyer et al., 1992).

Depending on the required accuracy, the unknown parameters can be determined by employing either a single image resection or a multiple image bundle adjustment. In both cases the camera calibration model is based on the well-known photogrammetric collinearity equation (Fraser, 1997). A detailed investigation of the aforementioned methods in the special case of a CCD camera mounted on a laser scanner is found in Wendt and Dold (2005).

2.2. Coordinate correspondence

The coordinate correspondence between scanner coordinates (i.e. object coordinates) and image coordinates involves two separate problems. Object coordinates should be transformed to image coordinates and image coordinates back-projected to object coordinates. The first case is straightforward and is expressed by the collinearity equations:

$$\begin{aligned} x_i &= -f\,\frac{R_{11}(X-X_0)+R_{12}(Y-Y_0)+R_{13}(Z-Z_0)}{R_{31}(X-X_0)+R_{32}(Y-Y_0)+R_{33}(Z-Z_0)}+\Delta x \\ y_i &= -f\,\frac{R_{21}(X-X_0)+R_{22}(Y-Y_0)+R_{23}(Z-Z_0)}{R_{31}(X-X_0)+R_{32}(Y-Y_0)+R_{33}(Z-Z_0)}+\Delta y \end{aligned} \tag{1}$$

where x_i, y_i are the image coordinates of an object point (X,Y,Z), X_o,Y_o,Z_o are the coordinates of the perspective center of the camera lens in the laser scanner coordinate system, f is the camera focal length, R_{ij} are the elements of the rotation matrix and Δx,Δy are the additional correction terms from the interior orientation. By using the equations (1) a colour value from the acquired image can be assigned to each measured 3D point. The aim is to simplify the processing of the laser data, because it is easier to relate coloured points to objects.

The second case refers to the reverse process, i.e. to determine the object coordinates (X,Y,Z) from the image coordinates x_i, y_i. This is much more complicated since the 3D information is lost in the image projection and the equations (1) are not sufficient to calculate the three unknown coordinates. To complement the missing information a 3D surface model of the object is used. The object coordinates that correspond to the given image coordinates are calculated from the intersection of the object surface with a view ray, starting from the camera focal point and targeting to the object point. The problem is to intersect the view ray with the 3D surface model, which is known as the single-ray back-projection problem.

There are two methods to solving the back-projection problem: the iterative photogrammetric method and the ray-tracing method. The first is widely used in photogrammetry while the second is popular in computer graphics. A detailed description for both can be found in Sheng (2004). In case of dense 3D surface models created from laser scanner measurements the ray-tracing method is more suitable and will be further explained.

For a given pixel in the image, a view ray R is defined by its origin (i.e. the camera focal point) $R_o = [X_o\ Y_o\ Z_o]^T$ and its normalized direction vector $R_d = [X_d\ Y_d\ Z_d]^T$:

$$R(t) = \begin{pmatrix} X(t) \\ Y(t) \\ Z(t) \end{pmatrix} = R_0 + t \cdot R_d = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + t \cdot \begin{pmatrix} X_d \\ Y_d \\ Z_d \end{pmatrix} \tag{2}$$

Where t is the distance between a point R(t) on the ray and the origin R_o. To calculate the direction vector R_d the inverse for of the collinearity equation is used:

$$\begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} = \frac{1}{\lambda} R^{-1} \begin{pmatrix} x_i \\ y_i \\ -f \end{pmatrix} \tag{3}$$

From equations (2) and (3) the direction vector of the ray can be calculated from image coordinates x_i, y_i:

$$\begin{pmatrix} X_d \\ Y_d \\ Z_d \end{pmatrix} = \frac{1}{t} \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} = \frac{1}{(\lambda \cdot t)} \cdot R^{-1} \cdot \begin{pmatrix} x_i \\ y_i \\ -f \end{pmatrix} = \frac{1}{(\lambda \cdot t)} \cdot \begin{pmatrix} R_{11}x_i + R_{21}y_i - R_{31}f \\ R_{12}x_i + R_{22}y_i - R_{32}f \\ R_{13}x_i + R_{23}y_i - R_{33}f \end{pmatrix} \tag{4}$$

The intersection of the view ray with the object surface is reduced to a ray – triangle intersection problem. For this purpose the object surface should be represented as a triangulated mesh. The use of triangulated meshes is not always necessary and alternative methods to calculate ray – surface intersections directly on the point cloud have been proposed (Tournas and Tsakiri, 2007; Ressl et al., 2006).

2.3. Control point identification

The identification of control points is carried out on the available images. Their object coordinates in the point cloud reference system are then calculated from the image coordinates, as explained in the previous section. The first issue is the availability of invariant features that can be identified from different views. Assuming that sufficient texture variations exist on the images, several methods may be employed to extract distinct edges or corners. In this work, the Harris Interest Operator is used (Harris and Stephen, 1998).

A large number of candidate control points may be initially pointed out in the overlapping area of the images. Since a limited number of them are necessary for the registration, only the stronger points within a minimum distance of 50 pixels to each other are reserved. The next step is to calculate the corresponding object coordinates. This may not be feasible for all selected points, because some areas visible on the images may not be available on the point cloud. This is due to the eccentricity between the two devices witch they do not share the same point of view. In addition, points located on geometrically discontinuous areas should be eliminated from the sample. That is why points positioned on plane areas can ensure reliable solutions in the ray-surface intersection problem and are more adequate for image matching operations.

When a sufficient set of candidate control points is accepted on each image, an image matching procedure is employed to find the correspondences between the two views. In cases with a relatively small number of points all possibilities of combinations may be checked. A sophisticated approach for the control point correspondence problem that can cope with a large number of points is presented in Wendt (2004). In this work all possibilities of combinations are checked using the Least Squares Matching process (Gruen, 1985). The matching procedure is considerably accelerated when the first three correspondences are found. Three common points are sufficient to calculate an initial solution for the absolute orientation problem that allows point transformations between the two point clouds. In brief, the following strategy is adopted:

- the object coordinates X_a, Y_a, Z_a of a candidate control point of the first point cloud are transformed to the second point cloud X'_b, Y'_b, Z'_b using the initial transformation parameters
- the object coordinates X'_b, Y'_b, Z'_b are projected on the image of the second point cloud at x'_b, y'_b (eq. 1)
- the image coordinates x'_b, y'_b are used as initial values in the Least Square Matching procedure to calculate more accurate x_b, y_b coordinates
- new X_b, Y_b, Z_b object coordinates are calculated from the image coordinates x_b, y_b
- a new solution for the absolute orientation is calculated including the new point X_b, Y_b, Z_b

The above procedure is repeated until all control points identified on the first image are transferred to the second. The final solution can be further improved by checking the residual errors of the control points used and eliminating points with gross or unacceptable errors.

3. IMPLEMENTATION

The effectiveness of the proposed methodology was investigated also experimentally using a Nikon 4700 CCD camera that was externally mounted on top of a Cyrax 2500 laser scanner. The laboratory experiment was performed on a model of 1:3 scale replica of an ancient temple exposed to controlled earthquake vibrations. The particular structures are of interest because they present a complicated response as a result of the way they are built; made by carefully fitted stones, which lie on top of each other without mortar and during a strong earthquake, the stones can slide and/or rock independently or in groups (Mouzakis et al., 2002). The experiment was carried out on the shaking table facility of the Laboratory for Earthquake Engineering of the National Technical University of Athens. The table has dimensions 4m×4m and can move in all six degrees of freedom. The maximum displacement that can be achieved is ± 0.10m in each direction and the maximum acceleration is 2g in each horizontal direction and 4g in the vertical. The operating frequencies in each degree of freedom range from 0.1 to 50 Hz. During the experiments, several earthquake motions scaled appropriately in order to trigger significant rocking but no collapse of the model were used as the excitation.

Two overlapping point clouds were captured before and after the earthquake stress (figures 1a, b). The scanning resolution was set at 0.01m at a distance of 10m. The two scans were executed from different views, by applying translation and rotation movements to the scanner device after the first scan acquisition.

The system calibration was performed on a calibration field with 56 signalised control points. From these points, 14 were properly signalised with retro-reflective targets which are automatically recognised by the Cyrax 2500 proprietary software. The targets were placed in different planes, with a maximum vertical relief of 4m. The target coordinates were calculated with theodolite measurements at an accuracy of ±1mm, in an arbitrary coordinate system. The calibration field was captured by both the laser scanner and the CCD camera. The resolution of the image acquired by the CCD camera was 2592×1944 pixels. The 14 retro-reflective targets were measured separately using the laser scanner, with the maximum possible accuracy of ±1mm. The interior orientation of the CCD camera was estimated by a self-calibrating photogrammetric resection, using all available target points. The exterior orientation of the image was found with the use of the 14 retro-reflective targets. The translation parameters of the camera relative to the laser scanner were $D_x = 0.019$ m, $D_y = 0.199$ m and $D_z = -0.252$ m. The rotation angles about the X, Y, Z axes were $\theta_x = -0.040832$ rad, $\theta_y = 0.000856$ rad and $\theta_z = 0.004351$ rad, respectively.

(a) (b)

Figure 1 - Scanner acquisitions (a) before and (b) after the earthquake stress

(a) (b)

Figure 2 -: (a) Initial and (b) finally kept control points

The identification of candidate control points on the overlapping area of the two scans was carried out by the use of a Harris Interest Operator. From the 66 points initially selected, 8 control points satisfying the criteria of section 2.3 were finally kept (figures 2a, b). The object coordinates of these points were calculated using the direct ray – point cloud intersection method described in Tournas and Tsakiri (2007). The coordinates of the control points as well as the remaining errors of the absolute orientation between the two scans are presented in table 1. The translation parameters between the two systems were D_x = -0.204 m, D_y = 0.007 m and D_z = 0.265 m. The rotation angles about the X, Y, Z axes were θ_x = -4.255721 grad, θ_y = -4.459959 grad and θ_z = 3.153669 grad respectively.

The registration accuracy was better than 2 mm in X, Y direction and 3 mm in Z. The accuracy is acceptable for the project requirements and is comparable to the accuracies achieved with the use of signalized targets. The second point cloud was transformed to the coordinate system of the first. At the end, the specimen was extracted from the point cloud in order to further examine possible deformations caused from the earthquake stress (figure 3).

	1st scan			2nd scan			Residual errors (m)		
id	X	Y	Z	X	Y	Z	ΔX	ΔY	ΔZ
1	1.0648	-1.3821	-12.6812	2.2425	-2.1822	-12.7116	-0.002	0.002	0.004
2	-1.7554	-1.5534	-12.4542	-0.5768	-2.4871	-12.6549	-0.001	0.000	-0.002
3	-0.9576	1.5032	-12.5486	0.0718	0.5968	-12.9121	0.001	-0.002	-0.001
4	-1.9323	0.8005	-12.5425	-0.8655	-0.1575	-12.9219	0.002	0.000	0.000
5	1.1067	1.6690	-12.8227	2.1408	0.8558	-13.0614	0.001	-0.002	0.001
6	3.8818	3.9016	-18.8627	5.2199	2.8252	-19.0443	0.000	0.001	-0.001
7	3.9669	0.8993	-18.8984	5.4563	-0.1632	-18.8647	-0.001	0.000	0.000
8	-3.5340	1.0681	-12.3705	-2.4855	0.0340	-12.8757	0.000	0.000	0.000

Table 1 - Control point coordinates and residuals (in m)

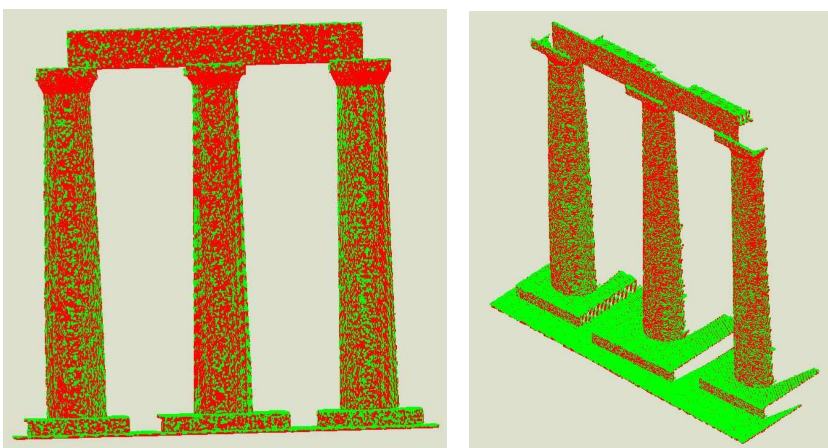

Figure 3 - Object of interest after point cloud registration

Having obtained the registered point cloud of the object, and in order to calculate displacements before and after the earthquake excitations simulated by the shaking table, 11 control points were identified on the object surface, i.e. on the facades of the three pillars. The coordinates of the selected control points were calculated twice, as shown in table 2, before (x, y, z) and after (X, Y, Z) the excitation. The comparison between the two coordinate sets of table 2 in the laser scanner coordinate system indicates that the excitation is significant at the longitudinal direction and less significant at the lateral direction, whilst the vertical direction presents motions that can be assumed insignificant as they are within the expected noise levels of the laser scanner data. The results are as expected as plane motion was applied for the excitation.

	Before excitation			After excitation			Difference		
id	x	y	z	X	Y	Z	Δx	Δy	Δz
1	-1.591	-1.381	-8.053	-1.609	-1.376	-8.045	-0.017	0.005	0.007
2	-0.202	-1.357	-8.128	-0.215	-1.352	-8.127	-0.013	0.005	0.001
3	1.185	-1.340	-8.168	1.164	-1.332	-8.163	-0.022	0.007	0.005
4	-1.634	-0.066	-8.062	-1.644	-0.064	-8.061	-0.009	0.002	0.001
5	-0.228	-0.011	-8.146	-0.239	-0.007	-8.135	-0.011	0.004	0.011
6	1.184	-0.028	-8.178	1.169	-0.024	-8.169	-0.014	0.004	0.009
7	-1.681	1.253	-8.079	-1.701	1.261	-8.064	-0.020	0.008	0.015
8	-0.265	1.273	-8.160	-0.275	1.276	-8.154	-0.010	0.004	0.006
9	1.123	1.323	-8.176	1.118	1.325	-8.168	-0.005	0.002	0.008
10	-0.994	1.776	-8.074	-1.008	1.780	-8.071	-0.015	0.004	0.002
11	0.435	1.818	-8.128	0.423	1.822	-8.117	-0.012	0.003	0.011

Table 2 - Deformation monitoring (in m)

4. CONCLUSIONS

Registration of point clouds requiring high accuracy results can only be achieved using special targets which must be placed at selected locations on the surface of the scanned object. This is because current proprietary laser scanner software recognises such targets automatically and with the aid of surveying measurements, rigid body transformation is performed to convert all scans into a global coordinate system.

An alternative method presented in this paper makes use of photographic images obtained during the laser scan acquisition to perform point cloud registration. The only requirement is to execute a calibration process due to the fact that the external CCD camera that is used along with the scanner device is non-metric. The use of external images facilitate the identification of control points whereby their image coordinates are directly used to calculate corresponding 3D object coordinates.

The proposed method provides results of satisfactory accuracy required in the majority of typical laser scanning applications and can be of special interest to objects that are prohibitive to making use of special signalised targets, such as tall buildings or objects with complex surfaces. It is also appropriate for deformation monitoring in cases where the surrounding environment remains stable, as is the case study presented in this work.

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