AUTOMATIC 3D POINT CLOUD REGISTRATION FOR CULTURAL HERITAGE DOCUMENTATION

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ABSTRACT:

Terrestrial laser scanning is a recognised technique for the geometric documentation of objects and surfaces in a variety of applications but the amount of information acquired by laser scanners makes the registration of pairs and multiple scans a complex problem. Thus, the general scanning practice still requires the use of signalised targets placed at selected locations on the surface of the scanned object. In this paper a methodology for point cloud registration via image-based information and without the use of targets is presented. For this purpose, a specific number of control points located on the object surface are used. These points are identified automatically on photographic images taken during laser scanner data acquisition from an external high resolution CCD camera mounted on the scanner device. Following the presentation of the method, the application on the documentation of a cultural heritage building is described.

1. INTRODUCTION

The use of terrestrial laser scanners in documenting large objects and sites, such as in cultural heritage applications, has significantly increased over recent years. This is mainly due to the fact that laser scanning can provide high productivity on creating dense surface models in a short period of time. High resolution geometric models can be derived from laser scanning data and 3D recordings and virtual presentations can be produced as final products.

Due to visibility constrains from single laser scanner acquisition, it is often necessary to combine multiple overlapping point clouds into a single data set to fully cover the object being surveyed. This procedure is usually referred to as registration and it involves determination of the transformation parameters between the local coordinate systems of the point clouds such that all can be transformed into a common coordinate system. The transformation parameters can be easily estimated if at least three common points can be identified on the overlapping area.

In many applications related to documentation of cultural heritage monuments it is necessary to scan inaccessible objects ensuring high automation. In these cases, the registration cannot be performed without using signalised targets. The automatic registration of point clouds without the use of targets is an active area of research. The methods found in the literature 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 correspondences are assigned between the measured objects (Remondino, 2004; Rabbani et al. 2007). 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 works well if good a priori alignment is provided, otherwise it may not converge. However, in the case of registering 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. Furthermore, the main disadvantage of the ICP-algorithm is its disability to align point clouds with different resolutions, noise or with a small overlap. Several variants of the ICP algorithm have been proposed to overcome the aforementioned limitations. For example, Bae and Lichti (2004, 2008) provide an improvement of the ICP algorithm by finding corresponding points in an automatic manner.

A third category of methods for the registration of point clouds involves the use of external information, in the form of photographic images taken from a high resolution CCD camera mounted on the scanner device. 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 this notion, a methodology for registering overlapping point clouds without the use of targets but with the use of external images, has been developed and is presented in this paper. The proposed methodology can be of special interest to objects where placement of special signalised targets is difficult, such as tall buildings or objects with complex surfaces. For this purpose, a sufficient number of common points located in the overlapping area 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

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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. Section 2 of the paper presents the proposed methodology, giving emphasis to the essential steps required for its implementation. Section 3 presents a case study pertaining to the documentation of a cultural heritage site, in particular the famous Byzantine Monastery of Hossios Lukas, whereby the proposed automatic registration method of overlapping point clouds is implemented. Finally, section 4 summarises the work and provides concluding remarks.

2. METHODOLOGY

The aim of the proposed methodology is the automatic registration of overlapping point clouds using external information acquired from corresponding images. The registration process involves the identification of sufficient 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 photographs acquired together with the point clouds, from the same point of view. 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; therefore seven unknown parameters have to be estimated. Three control points with known coordinates in both systems are sufficient 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). In the following, the basic steps of the proposed methodology, i.e. calibration, coordinate transformation, and control point identification, are described.

2.1 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.

It is usually assumed that the origin of the camera coordinate system coincides with the centre of projection and that the line of sight is aligned to the Z axes (Forkuo and King, 2004). In general, the CCD camera is displaced and rotated with respect to the three-dimensional laser scanner coordinate system and the coordinates (x_l, y_l, z_l) of the laser coordinate system must be transformed to the coordinates (x_c, y_c, z_c) of the point in the camera coordinate system before projecting the points onto the image plane (Figure 1).

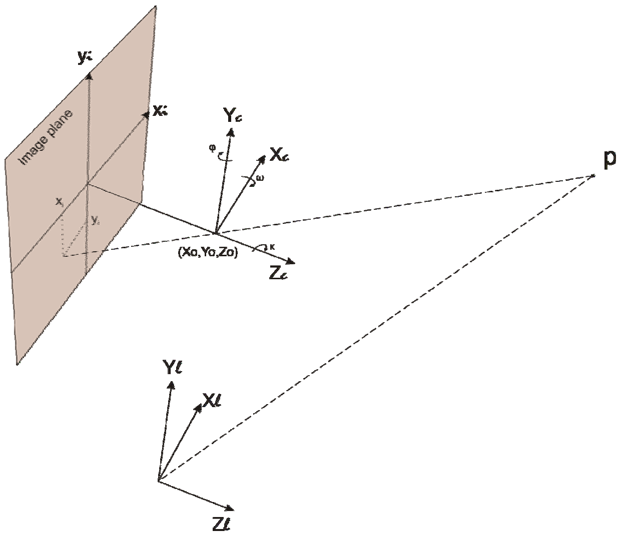

Figure 1: Laser scanner – image coordinate systems

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_o,Y_o,Z_o) of the perspective centre of the camera lens and the three rotation angles (ω,φ,κ) 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 collinearity equations (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 transformations

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:

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

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 centre 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 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 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 perspective centre 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 backprojection problem.

There are two methods to solving the backprojection 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 of both of them 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 V is defined by its origin (i.e. the camera focal point) $V_o = [X_o\ Y_o\ Z_o]^T$ and its normalized direction vector $V_d = [X_d\ Y_d\ Z_d]^T$:

$$V(t) = \begin{pmatrix} X(t) \\ Y(t) \\ Z(t) \end{pmatrix} = V_0 + t\cdot V_d = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + t\cdot\begin{pmatrix} X_d \\ Y_d \\ Z_d \end{pmatrix} \qquad (2)$$

where t is the distance between a point V(t) on the ray and the origin V_o. To calculate the direction vector V_d the inverse of the collinearity equation is used:

$$\begin{pmatrix} X-X_0 \\ Y-Y_0 \\ Z-Z_0 \end{pmatrix} = \frac{1}{\lambda}R^{-1}\begin{pmatrix} x_i \\ y_i \\ -c \end{pmatrix} \qquad (3)$$

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

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

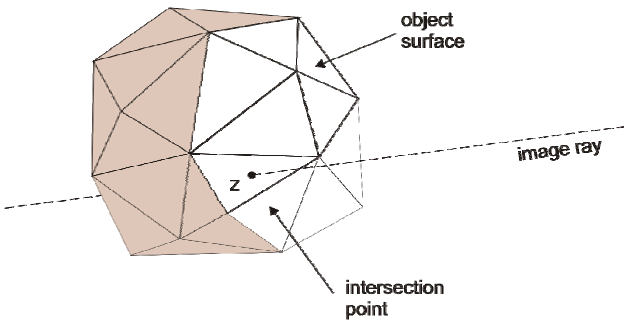

Figure 2: Image ray intersection with mesh

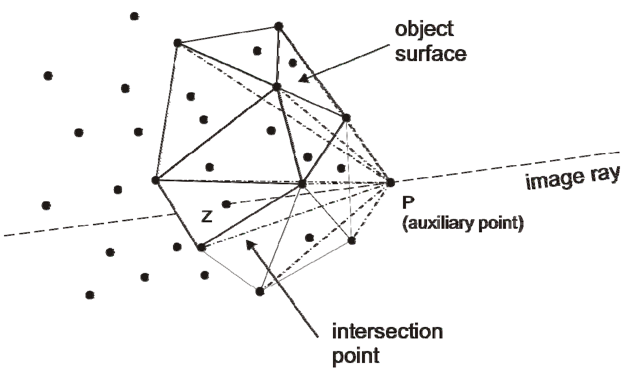

Figure 3: Ray intersection directly to the point cloud

The intersection of the view ray with the object surface becomes a ray – triangle intersection problem (Figure 2). For this purpose the object surface should be represented as a triangulated mesh. The use of triangulated meshes is necessary because point cloud representations do not contain any information about point connectivity. However, the creation of a triangulated mesh is not always a fully automated process especially in cases of complex surfaces with sudden depth variations.

An alternative method to calculate ray – surface intersections directly on the point cloud has been proposed by Tournas and Tsakiri (2007) for orthophoto generation from unorganized point clouds. In this method the intersection ray is perpendicular to the orthophoto plane which is usually the XY plane of the laser scanner coordinate reference system. In the present paper, the existing algorithm has been improved, to be independent of image ray orientation.

Since a point cloud representation does not contain any information apart from point location, the connectivity of points in a local environment near to the image ray should be refined. To find an appropriate environment, which actually represents a small part of the object's surface it is assumed that the closest points to the image ray contribute to this environment. It is also assumed that the sampling rate is high, which in practice is achieved with the laser scanner. The intersection point is computed by the intersection of the image ray with the smallest triangle defined by three points of the point cloud, on the topmost object surface. In the simplest situation, a unique and suitable triangle is defined by the three points closest to the image ray V; however this is not the usual case. In a composite scene with significant depth variations, a great number of points may be close to the ray but it is not guaranteed that the triangle formed by the three closest points belongs necessarily to the topmost object surface.

To locate the correct triangle, all points that are close to the image ray should be examined. For this purpose, the nearest points to the ray are extracted from the point cloud by defining an appropriate distance threshold. For each point of the selected point set, its projection on the image ray is calculated and the point with the shortest projection length is identified. It is clear that the intersection point cannot be closest to the ray origin (i.e. to the projection centre) than the shortest projection length. To investigate the triangle faces on the topmost object surface, an auxiliary point P is introduced (Figure 3). This point is lying on the image ray at a distance equal (or less, to avoid coplanarity issues) to the shortest projection length. The appropriate triangle is identified by applying a local Delaunay tetrahedrization near the auxiliary point P. The implementation of this algorithm is explained in detail in Tournas and Tsakiri (2007).

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 detected in the overlapping area of the images. Since a limited number of points 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 which they do not share the same point of view. In addition, points located on geometrically discontinuous areas should be eliminated from the sample. Hence, points lying on plane areas force in more reliable solutions in the ray-surface intersection problem and are more adequate for image matching operations.

When an efficient set of candidate control points is accepted for each image, an image matching procedure is employed to find the correspondences between the two views. In the case of 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 (LSM) 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. Any candidate control point from the first point cloud can be transformed to the coordinate system of the second, using the initial solution for the absolute orientation. The corresponding image coordinates are then calculated in the second image using equation (1).

Figure 4: Initially identified control points

Since the transformation parameters may not be sufficiently accurate, the image coordinates will not be sited exactly on the control point. To improve the accuracy, the LSM process is employed using the calculated image coordinates as initial values. The object coordinates are then recalculated using the method presented in section 2.2, and a new estimation of the absolute orientation is executed using new control points. The same procedure continues until all candidate control points are introduced into the absolute orientation computation.

3. CASE STUDY

The proposed methodology has been tested using laser scanner data acquired for the geometric documentation of the Byzantine Monastery of Hossios Lukas, in Greece. Hossios Lucas is a historic walled monastery situated near the town of Distomo, in Boeotia, Greece. It is one of the most important monuments of Middle Byzantine architecture and art, and has been listed on UNESCO’s World Heritage Sites in Greece, along with the monasteries of Nea Moni and Daphnion.

Two overlapping point clouds were captured on the north side of the Katholikon, using an HDS2500 laser scanner with a Nikon 4700 CCD camera mounted on top of the scanner. The scanning resolution was set at 0.01m at a distance of 10m. The two scans were acquired 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 HDS2500 scanner 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 2592x1944 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 estimated using the 14 retro-reflective targets.

The translation parameters of the camera relative to the laser scanner were estimated as $D_x = 0.005$ m, $D_y = 0.210$ m and $D_z = -0.237$ m. The rotation angles about the X, Y, Z axes were estimated as $\theta_x = 0.03336$ rad, $\theta_y = 0.00963$ rad and $\theta_z = 0.01958$ rad, respectively.

Figure 5: Finally accepted control points (1st scan)

Figure 6: Finally accepted control points (2nd scan)

The identification of the candidate control points on the overlapping area of the two scans was carried out by the use of a Harris interest operator. From the 59 points initially selected (shown in red colour in Figure 4), 11 control points satisfying the criteria of section 2.3 were finally kept (Figures 5 and 6).

The object coordinates of these points (given in Table 1 in units of meters) were calculated using the direct ray – point cloud intersection method as described in section 2.2. The second point cloud was transformed to the coordinate system of the first. The translation parameters between the two systems were estimated as $D_x = 0.009$ m, $D_y = 0.008$ m and $D_z = 0.032$ m. The rotation angles about the X, Y, Z axes were $\theta_x = -30.7503$ grad, $\theta_y = -0.4011$ grad and $\theta_z = -0.0943$ grad, respectively. The mean registration error (RMSE) was 1.7 mm and 1.6 mm in X, Y directions and 2.4 mm in Z direction. The residual errors in mm calculated at each control point (CP) are shown in Table 2. The obtained accuracy is acceptable for the project requirements and is comparable to the accuracies achieved by the use of signalized targets.

CP	X1	Y1	Z1	X2	Y2	Z2
1	-2.190	-2.522	-8.595	-2.235	1.761	-8.727
2	-1.856	-1.680	-9.241	-1.906	2.810	-8.916
3	1.354	-1.628	-9.351	1.302	2.911	-9.009
4	1.499	-2.322	-8.962	1.446	2.114	-8.986
5	-0.823	-2.439	-8.809	-0.871	1.939	-8.892
6	0.317	-2.307	-8.896	0.266	2.096	-8.911
7	-1.434	-2.280	-8.976	-1.483	2.155	-8.961
8	-0.705	-1.492	-9.346	-0.759	3.027	-8.926
9	-2.283	-1.901	-8.518	-2.328	2.275	-8.376
10	1.729	-1.863	-8.593	1.678	2.347	-8.441
11	1.721	-2.541	-8.644	1.673	1.773	-8.807

Table 1: CP coordinates after interpolation (point clouds 1 & 2)

CP	Sx (m)	Sy (m)	Sz (m)
1	0.003	-0.002	0.004
2	-0.001	0.002	-0.002
3	0.001	0.001	-0.003
4	-0.002	-0.001	-0.001
5	0.001	0.001	-0.002
6	-0.000	0.001	0.002
7	0.001	0.000	-0.000
8	-0.003	0.003	0.001
9	0.001	-0.002	-0.002
10	-0.002	-0.003	0.005
11	0.002	-0.001	-0.002

Table 2: Residual errors of the control points

From the above investigation it is seen that accurate point cloud registration can be achieved using external information from registered images, without the need of signalized targets. However, there is a question regarding the feasibility of indentifying control points on overlapping images in cases of complex buildings and point clouds obtained with greater angles of divergence. In the examined case, the convergence angle of about 30 gradients relative to the X axis does not influence the efficiency of the least square matching, but it is well known that the LSM algorithm cannot be used in cases of high convergence angles and high scale differences between the overlapping images. In such cases, more sophisticated approaches should be employed, such as SIFT operators that can give satisfactory results (Lingua et al., 2009). The suitability of the SIFT technique for automatic tie point extraction and the assessment of the accuracy is within the future directions of this work.

4. CONCLUDING REMARKS

In documentation applications which require high accuracy results, it is necessary to use special targets which are placed at selected locations on the surface of the scanned object. This is due to the fact that the registration algorithms used in proprietary laser scanner software recognise the special targets automatically and with the aid of external surveying measurements they perform a rigid body transformation in order to convert all scans into a common coordinate system.

The automatic registration of point clouds without the use of targets is an active area of research. A method of automatic registration has been presented in this paper which makes use of external information in the form of photographic images obtained during the laser scan acquisition. The basic 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 facilitates 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 site documentation applications. The implementation of the method in registering scans acquired from the external surfaces of the Byzantine church of Hossios Lukas gave results of better than 2-3 mm. Clearly, the method can be of special interest to objects where placement of special signalised targets is difficult, such as tall buildings or objects with complex surfaces.

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