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An Accurate 3D Point Cloud Registration Approach for the Turntable-based 3D Scanning System

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***Abstract* – Registration of 3D point clouds is an important issue in 3D scanning domain. In this work, we developed a turntable-base structured light system for the automatically 3ED scanning purpose. To realize the fully automatically 3D point clouds registration, a planar surface is placed on the turntable and scanned with different rotation angles. The turntable axis direction vector is calculated by averaging the intersection lines of the reconstructed planes firstly. And the linear minimization function is constructed for the robust and accurate estimation of the turntable origin. A variety of objects are used in the experiment. And the results show that, point clouds under different scanning angles can be precisely registered. In addition, there are no iterative procedures in the proposed algorithm, and that makes the registration procedure more efficiently.**

Index Terms – 3D registration, 3D scanning, structured light, turntable calibration.

I. INTRODUCTION

Non-contact optical 3D measurement has been widely used in a variety of applications, such as the industrial inspection, biometrics, human-machine-interaction, and virtual reality etc. [1]. According to the principle of optical 3D instrumentations, they can be generally classified into laser 3D scanning, structured light scanning (SLS) and Time of Flight (TOF) techniques. In comparison, the SLS technology is the most widely researched and adopted in real applications for its simplicity, accuracy and scanning efficiency [2].

A basic SLS system can be composed with a pair of camera and projector. In its working procedure, some pre-encoded pattern images are projected onto the target surface and captured by the camera synchronously. And then, the decoding procedure is applied to the captured images to extract the pattern features so as to establish intensive correspondences between camera and projector sensor planes. Finally, the triangulation process is applied to the correspondences for their depths calculation with reference to the system calibration parameters [3]. Obviously, a single scanning can only provide one set of 3D information at the fixed scanning view-point. If the user wants a complete 3D model, the target should be scanned from various viewpoints. And that caused the problem of 3D registration of various point clouds. To solve this problem, a popular and practical means is to stick some markers on the target surface. That makes the whole scanning procedure more complicate and lack for scanning efficiency.

In this work, a turntable-based SLS system was founded. The object is rotated with a fixed rotation angle and is scanned by the SLS. The pending crucial issue is to realize accurate and automatically registrations of multiple 3D scanning point clouds. With a simple analysis of the turntable-based scanning system, we can find that, the object should rotate with respect to the turntable axis perfectly without consideration of the turntable rotating deviations. If we can compute the rotation axis accurately with respect to the SLS coordinate system, the 3D registration issue can be greatly simplified. Based on such a motivation, a planar surface is mounted on the turntable. By rotating the plane and scanning its surface with various rotation angles, a simple geometrical calculation is applied to estimate position of the rotation axis. The methodology is simple and the calculation result is very robust. Experimental results showed that, multiple scanning point clouds can be precisely registered. And the whole computation is also very efficiently, since there are no iterative matching processes like traditional ICP-based algorithms adopted [4].

The organization of this paper is as follow. Previous works on the 3D registration of turntable-based 3D scanning systems are briefly reviewed in Section II. The proposed turntable axis calculation algorithm is introduced in Section III. Experimental results are provided and discussed in Section IV. Conclusion and potential future works are offered in Section V.

II. RELATED WORKS

Estimation of the rotation axis is a common issue for all the turntable-based 3D scanning system including both SLS system and laser scanning systems. These methods can be generally divided into two classes: the marker-based method and the tool-free method.

In [5], the author used a checkerboard to calculate the rotation axis. The checkerboard corner points are first detected and their 3D coordinates are calculated. Give a set of 3D feature points under different scanning viewpoints, the turntable axis direction was computed by solving an over-determined linear equation. In [6], a color-marked chessboard was used to calculate extrinsic parameters of the SLS device and the checkerboard plane in each scan. Since the SLS device is fixed and the checkboard plane is movable, the rotation axis can be calculated from various extrinsic parameters with respect to the SLS coordinate system. For these approaches,

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the major calculation error came from the corner feature detection error as well as the system calibration errors.

Some researchers adopted the standard geometric objects as the reference to calculate the rotation axis, such as a cube, a sphere or a plane. In [7], a sphere object was used. The sphere was mounted far away from the rotation center and scanned by rotating the turntable. For each rotation, the sphere was scanned and then fitted by a sphere equation to detect the sphere center points. By fitting multiple sphere center points with a circle, the circle center and normal vector were calculated to define the rotation axis. However, the accumulated fitting residuals may make definite effect to the final calculation results. In [8], four feature points were detected from the reference object, and there 4-points congruent sets were used for the automatic registration. For each pair of given scanning point clouds, a rotation matrix and initial rotation axis of turntable was firstly estimated by the giving points. And then, an iterative procedure was conducted to optimize the initial axis by estimating a rotation. In [9], a simple planar surface was adopted. And then, the plane was reconstructed multiple times during the scanning procedure. By fitting the scanned planar surface and their intersection lines can be calculated as the initial rotation axis. To refine the primary calculation results, a classical ICP algorithm was introduced. The major disadvantage of this approach is that, the plane should be precisely placed at the turntable center, so as to provide satisfied initial parameters for the consequent ICP algorithms. There are two disadvantage of above method: the plane must exactly manual place cross the turntable center and ICP is well-known slow convergence speed. In next section, we will introduce our method in detail.

In our method, the solution is much more practical and robust. A planar surface without any markers is used as the reference targets. It is not required to be placed across the turntable center. By rotating the plane surface several times, multiple 3D scanning point clouds can be obtained. Based on following observations: the turntable center has equal distance to each scanning plane, and the turntable axis is parallel with the intersection lines of various scanning planes, a linear optimization equation can be constructed to estimate the rotation axis accurately.

III. Calculation of Turntable Rotation Axis

Current manufacturing technologies can guarantee a very high precision of the electronic turntables. That means the rotation axis can be assumed perpendicular to the table surface. For this reason an 'L-shape' or a cube object is used in our experiment as shown by Fig. 1.

The planar object is placed on the turntable. There is a not requirement to its placement position. Empirically, it can be placed nearby the turntable center. By rotating the plane and scanning it each time, we can obtain a sequence of 3D point clouds $\mathbf{P}_i$. And then, a filtering procedure is applied to remove outliers and big noises in the point clouds. Finally, a least-square fitting planar method is applied each point set to compute the equation of each fitted planes as:

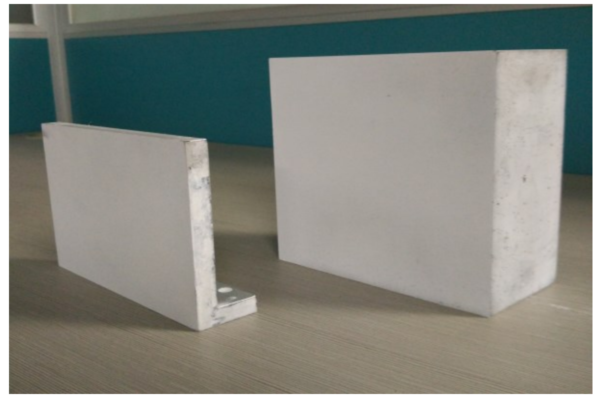

Fig. 1 An 'L-shape' plane or a cube is placed on the turntable and used as the reference plane.

$$A_i x + B_i y + C_i z + D_i = 0 \tag{1}$$

Based on the assumption that the reference plane is parallel with the rotation axis, directions of the plane intersection lines can be calculated as:

$$[n_x, n_y, n_z] = \frac{\sum_{i \prec j}^{n} \left|[A_i, B_i, C_i] \times [A_j, B_j, C_j]\right.}{n(n-1)/2} \tag{2}$$

where n indicates the direction vector of any two plane intersections. To determine the rotation axis, we only need to calculate the turntable center position $O(o_x, o_y, o_z)$.

Since the plane is fixed with respect to the turntable during the rotation and the turntable center $O(o_x, o_y, o_z)$ is also fixed with respect to the SLS device, the distance from $O(o_x, o_y, o_z)$ to the plane should be constant during various scanning processes. By using the rotation axis as normal vector, we can construct another group of planar equations as:

$$n_x x + n_y y + n_z z = 0 \tag{3}$$

The planes defined in (1) and (3) are perpendicular, so their intersection can be depicted by Fig. 2.

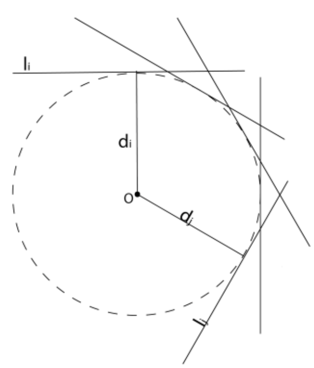

Fig. 2 The turntable center has equal distance to each scanning planes.

As shown by Fig.2, O refers to the turntable origin, l_i denotes the intersection line of plane in (1) and the constructed plane in (3). The equation of l_i is presented as:

$$\begin{cases} n_x x + n_y y + n_z z = 0 \\ A_i x + B_i y + C_i z + D_i = 0 \end{cases} \tag{4}$$

According to the basic geometrical knowledge, the distance between turntable center $O(o_x, o_y, o_z)$ to intersection lines l_i can be calculated as:

$$d_i = \frac{\left\| (n_x O_x + n_y O_y + n_z O_z)\vec{N}_i - (A_i O_x + B_i O_y + C_i O_z + D_i)\vec{N}_1 \right\|}{\left\| \vec{N}_1 \times \vec{N}_i \right\|} \tag{5}$$

where $\begin{cases} \vec{N}_1 = (n_x, n_y, n_z) \\ \vec{N}_i = (A_i, B_i, C_i) \end{cases}$.

Since the turntable origin is contained in the constructed plane, we can deduce the followed equation:

$$d_i = \frac{\left\| \vec{N}_1 \right\|}{\left\| \vec{N}_1 \times \vec{N}_i \right\|} \bullet (A_i O_x + B_i O_y + C_i O_z + D_i) \tag{6}$$

where the normal vector $\vec{N}_1, \vec{N}_2$, and the plane parameter A_i, B_i, C_i, D_i are known, so d_i can be solve via a linear equation. Since the distance from turntable origin to each plane is equal, i.e. d_i-d_{i+1}=0(i=1,…, n-1), we can get a matrix form linear equation as:

$$S_{n\times 3} \begin{bmatrix} o_x \\ o_y \\ o_z \end{bmatrix} = t_{n\times 1} \tag{7}$$

where S indicates the coefficients of vector $[O_x, O_y, O_z]^T$, and $t_{n\times 1}$ refers to the constant terms subtracted by Equation (6).

To solve the unknown parameters more accurately, the singular value decomposition (SVD) [10] method is firstly applied to (7) to get an initial positon of O. And then a linear minimization function is constructed as:

$$\min \sum_{i \neq j} \left| d_i - d_j \right| \qquad s.t. \qquad O = O_{init}$$

To solve this problem, we used the Matlab Optimization Toolbox, like the function *fminsearch* to get an optimization value of the turntable center position.

While the turntable axis has been calculated, the next step is to register the sequence of point clouds together to get a complete 3D scanning model. Supposed we have the original point cloud $P_{3\times n} = \begin{bmatrix} x_1, x_2 \cdots \\ y_1, y_2 \cdots \\ z_1, z_2 \cdots \end{bmatrix}$, we can rotate it around the calculated turntable axis with an angle θ and to obtain another point cloud $Q_{3\times n} = \begin{bmatrix} x'_1, x'_2 \cdots \\ y'_1, y'_2 \cdots \\ z'_1, z'_2 \cdots \end{bmatrix}$. For convenience, the MATLAB function *Rodrigues* is used for the point clouds transformation as:

$$Q_{3\times n} = rodrigues \cdot \left(\begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} \cdot \theta \right) \cdot \left(P_{3\times n} - \begin{bmatrix} o_x \\ o_y \\ o_z \end{bmatrix} \right) + \begin{bmatrix} o_x \\ o_y \\ o_z \end{bmatrix} \tag{8}$$

IV. EXPERIMENTAL RESULTS

The experimental setup is composed of one camera (with the resolution of 2080×1552 pixels, usb3.0 interface, focal length of lens is 10.0mm), one DLP projector (with the resolution of 1024×768 pixel, HDMI interface), and one electronic turntable with the rotate deviation about 0.01°. The distance between turntable and SLS device is about 700mm. The SLS is calibrated via the method in [11], and the structured light coding method in [12] is adopted. An I/O control board is developed to make the turntable and SLS device synchronically.

Fig. 3 Photo of the experimental setup.

An L-shape planar object is placed on the turntable nearby the turntable center. The rotation angle is set to 15°. The reference plane is rotated 8 times, so can we get 9 point clouds. After the preprocess of the point sets, the reconstructed planes are as shown by Fig. 4. By the fitting process, 9 planar equations can be calculated from the scanned point clouds. And then their intersection lines can be calculated. By averaging the computed intersection line directions, we can get the rotation axis direction vector $\vec{N}$. By adopting Equation (6-7), we can calculate the turntable origin position O. The calculation results are:

$$\vec{N} = [0.00091 \quad 0.98832 \quad -0.15238]^T$$

$$O = [-4.26833 \quad 119.89024 \quad 777.52998]^T$$

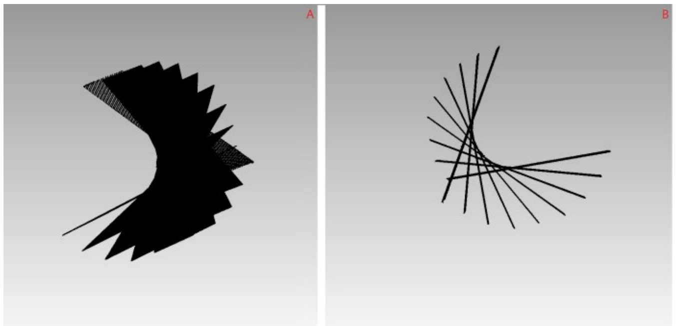

Fig. 4 The reference plane is rotated 8 times, we can get 9 point clouds of the planar surface.

To evaluate the calculation results, a plaster model with many details are used in the experiment as shown by Fig. 5. Left of Fig. 5 shows the original object surface. Right of Fig. 5 shows two adjacent scanning and registered points, which indicated by gray and red colors respectively.

Fig. 5 A plaster model with plentiful details is used for the experiment. And two adjacent scanning points are registered as shown by the right figure.

To implement a complete scanning process, we used a rotation angle of 60° for the model in Fig. 5. It needs six times of rotation. And the calculated rotation axis is applied for their registration. The reconstructed 3D model is as displayed at various viewpoints as shown by Fig. 6. For a close observation, details on the surface are enlarged and displayed by Fig. 7. From the results, we can see that, more detail can be preserved and registered precisely via the proposed method. More experiments with various objects are also provided in Fig. 8 to fully demonstrate the feasibility and accuracy of the proposed algorithm.

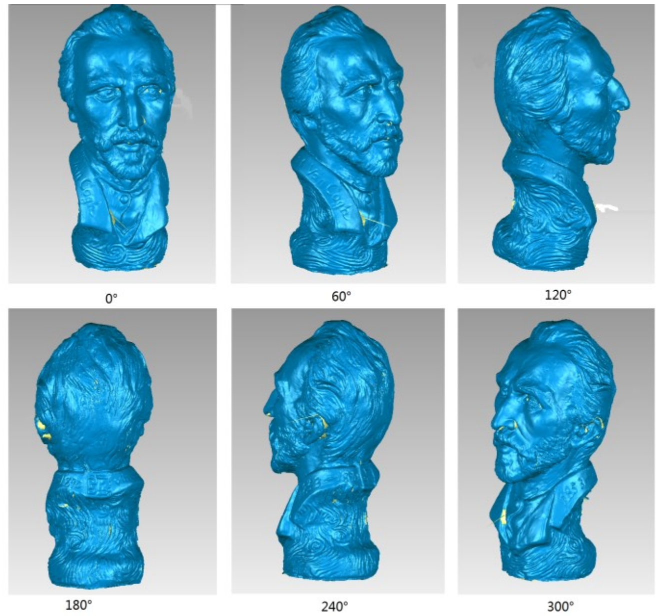

Fig. 6 The registered 3D model under different viewpoints.

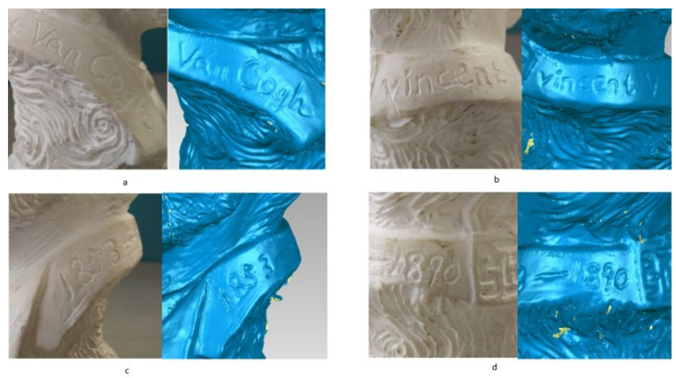

Fig. 7 Detailed feature on the model is enlarged for close observation.

Fig. 8 Registered 3D models of different object by the proposed method.

V. Conclusions and Future Work

In this paper, an accurate and practical method for the 3D point clouds registration is presented. The established 3D scanning system works with a turntable. A reference plane is put on the turntable and rotates several times to get a set of planar point set. By calculating the plane intersection lines, direction vector of the turntable axis can be estimated. And then, a linear minimization problem is constructed to estimate the turntable center position. Finally, the turntable axis can be fully determined with respect to the SLS coordinate system. And the various scanning point clouds with different rotation angles can be precisely and efficiently registered. Various experiments on different objects are implemented to show its feasibility and high registration accuracy. Future works can address how to merge the registered point clouds optimally, such as to boost the point cloud stitching quality by considering the surface normal factors.

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