International Journal of Multimedia and Ubiquitous Engineering
Vol.9, No.9 (2014), pp.109-116
http://dx.doi.org/10.14257/ijmue.2014.9.9.12

A Novel Multi-view Three-dimensional Visual Measurement Method Based On Hexahedron Targets

Beiyi Wang, Haibin Wu, Xiaoyang Yu*, Jixun Zhang and Junfeng Wu

The Higher Educational Key Laboratory for Measuring and Control Technology and Instrumentations of Heilongjiang province, Harbin University of Science and Technology, Harbin 150080, China
23402891@qq.com

Abstract

In order to meet the demand of coded light multi-view 3D reconstruction, we propose a highly efficient and accurate technique for point cloud registration, which can acquire the whole surface information of the measured piece without the help of other locating equipment. Method: First of all, we illustrate the principle of the hexahedron targets registration, establish the index point couples and present the registration patterns for each side of the target, as well as the recognition approach. Then, based on the quaternion preliminary registration, we propose an accurate registration method which combines the orthogonal Grey code and ICP. The result of the simulated experiment shows that the registration error of the hexahedron targets method is approximately 0.03mm, and during the actual experiment, the number is approximately 0.8mm, which is close to the global camera method and a little bit higher than the surface method. The new technique solves the problem that the measured surface cannot be placed with index points. Furthermore, this technique ensures the registration accuracy without any other apparatus.

Keywords*: coded light; point cloud registration; the orthogonal Grey code; hexahedron targets*

1. Introduction

Among the modern measuring techniques, coded light measurement has become an important method. Different from the traditional contact measurement, the coded light measurement avoids the subtle damage to the measured piece caused by the contact. However, to some huge measured pieces, the measurement cannot be finished at one time due to the restriction of the camera field range. We have to measure the piece partially and then unite all the partially measured data into one coordinate frame. This is 3D point cloud registration [1-3], a crucial technique to achieve the surface measurement of huge work pieces.

Nowadays, registration methods with high accuracy mainly include [4-5]: 1. **Precision machine registration**. We obtain the relations among each coordinate frame and directly record the translation and rotation parameters of the measured piece. Accurate as it is, this method is hard to achieve omnibearing registration of six degrees of freedom by only translating and rotating in a certain direction, which has a low efficiency. 2. **Optical apparatus registration**. The main apparatus in use are: laser tracker, optical theodolite, etc. Registration via optical or electromagnetic locating apparatus increases the complexity of the equipment, as well as introducing the error. For instance, the electromagnetic tracker is prone to be interfered by metal equipment, causing locating mistakes 3. **Index point registration**.

ISSN: 1975-0080 IJMUE

There are two different ways for index point registration. One is sticking the index points on the surface of the measured piece and getting the relations among different coordinate frames by tracking and matching the index points. For this method, it is not suitable for soft and fragile objects. Besides, the spots covered by the index points have color information losses. The other way is locating the index points on the surface of coded light device. With the addition of the global camera, the registration is achieved by tracking the coded light device. For this method, new apparatus is introduced, which increases the error factor and the complexity of the device.

Focusing on the features of the objects like ceramic and metal, we propose the principle of the hexahedron targets registration, establish the index point couples and carry out the preliminary registration based on the quaternion. Then, we start the accurate registration using ICP. In the process of the accurate registration, we develop a technique based on orthogonal edging Grey code to eliminate the incorrect point couples. Finally, we carry out the registration experiment and verify the registration result quantificational and qualitatively.

2. Principle of the Hexahedron Targets Registration

The hexahedron targets registration method we propose, as is shown in Figure 1, sets the index points on the auxiliary target. During the registration, put the target near the surface of the measured piece, make sure the relative location of the two objects is fixed (which is equal to setting the index points on the extension of the measured piece) and then we can finish the registration. The hexahedron target consists of six sides of which the location is fixed to each other. During the global measurement, the monocular camera can capture any side of the auxiliary target. Therefore, if we use the first row of the chessboard pattern of each side to code that side, then we can determine the side of the target on which the index points lie (shown in Figure 2).

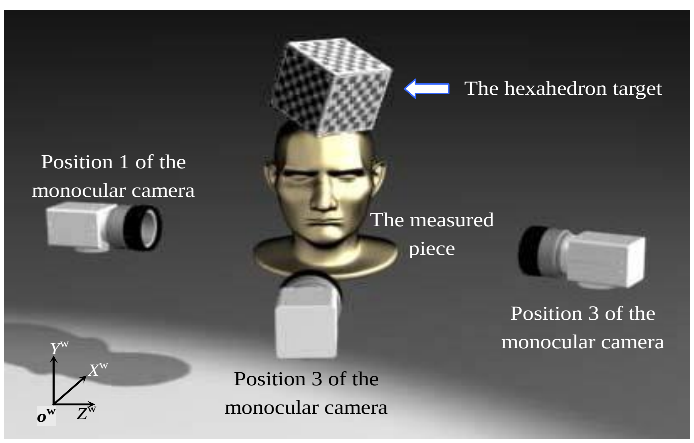


Figure 1. Hexahedron Target Method

The advantages of this technique include: 1. this technique solves the problem that the index points cannot be set on surface of the measured piece; 2.the index points are off the surface of the measured piece. We can adjust the original relative position of the measured piece and the target to make the index points close to the surface of the measured piece. 3. All six sides of the target are set with index points, so we can always have the images with the index points from any shooting angle. In spite of the fact that images from two adjacent measuring angles may not share the index points on the same side, we can still achieve the registration because we can obtain the spatial relations of the index points on different sides according to the code. This is especially important when the two adjacent measuring angles are too large. 4. This technique avoids the problem that all the index points are on the same plane and consequently avoids the abnormal solutions of the least square method or the misconvergence of the iteration method.

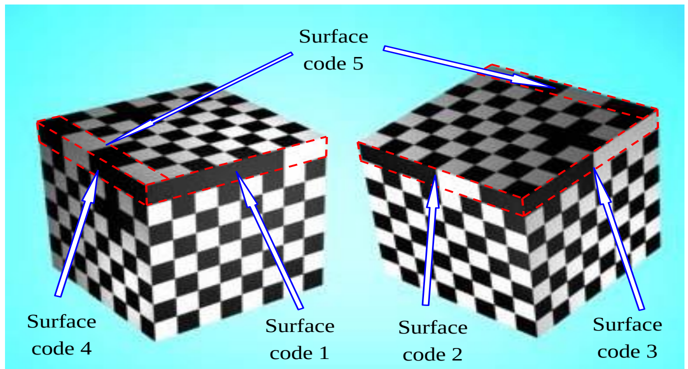


Figure 2. Coded Calibration Plane

3. Computing of the Transition Matrix

3.1. The Preliminary Registration

The quaternion uses a vector which includes four special elements to get the rotation matrix **R** and the translation matrix **T**. It can be seen as a combination of a 3x1 vector and a scalar. Usually, the quaternion is denoted by:

$$q = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \begin{bmatrix} q_{1,2,3} \\ q_4 \end{bmatrix} \tag{1}$$

where q1,2,3 can be seen as a 3 dimensional vector. Besides, the rotation vector R can be given by:

$$R = \left(q_4^2 - q^T qI + 2q^T q + 2q_4 K(q) \right) \tag{2}$$

where K is called antisymmetric matrix and we have:

$$K(q) = \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix} \tag{3}$$

In rigid body kinematics, the quaternion method is convenient to compute. Therefore, combined with ICP algorithm, it has been developed into a new algorithm to solve the original rotation matrix **R**, which can be described with 7 steps: 1. Respectively, compute the centroids $\mu = \frac{1}{N}\sum_{i=1}^{N} P_i$ and $\mu^{'} = \frac{1}{N}\sum_{i=1}^{N} X_i$ of the object points set $\{P_i\}$ and the model points set $\{X_i\}$; 2.Relative to the centroids, make the translations of the points set $\{P_i\}$ and $\{X_i\}$, which are denoted by $m_i = p_i - u_i$ and $m_i^{'} = x_i - u_i^{'}$; 3. Compute the relevant matrix K according to the after-translation points set $\{m_i\}$ and $\{m_i^{'}\}$, which can be presented as $K = \frac{1}{N}\sum_{i=1}^{N} m_i \left(m_i^{'}\right)^T$; 4. Construct a four dimensional symmetric matrix based on the elements $K_{ij}\left(i, j = 1,2,3,4\right)$ of the matrix K, which is given by

$$K = \begin{bmatrix} k_{11}+k_{12}+k_{13} & k_{32}-k_{23} & k_{13}-k_{31} & k_{21}-k_{12} \\ k_{32}-k_{23} & k_{11}-k_{22}-k_{33} & k_{12}+k_{21} & k_{13}+k_{31} \\ k_{13}-k_{31} & k_{12}+k_{21} & -k_{11}+k_{22}-k_{33} & k_{23}+k_{32} \\ k_{21}-k_{12} & k_{31}+k_{13} & k_{32}+k_{23} & -k_{11}-k_{22}+k_{33} \end{bmatrix} \tag{4}$$

5. Compute the unit eigenvector $q = \left[q_0, q_1, q_2, q_3\right]^T$ which is related to the maximum eigenvalue of K; 6. Compute the rotation matrix R based on the relation of q and R; 7. Compute the translation vector $T = \mu_i^{'} - R\mu_i$.

3.2. The Accurate Registration

The ICP algorithm is short for the Iterative Closest Points algorithm. Through defining an error function, the ICP algorithm reflects the goodness of fit for the overlapped region of the point cloud, which makes the objective function have the minimum value through optimizing the rotation and translation parameters [7-9]. The algorithm mainly includes four steps: 1) Sample the original point cloud data; 2) Determine the original related points set; 3) Eliminate the incorrect related point couples; 4) Solve the coordinates conversion.

Based on certain criteria, determine the related points sets P and Q and then compute the optimal transition matrix through the lease square method, which make the error function has the minimum value.

$$E(R,t) = \frac{1}{n}\sum_{k=1}^{n} \left\| q_k - (Rp_k + t) \right\|^2 \tag{5}$$

The ICP algorithm we proposed are basically as follows [10] :

1. Compute the original coordinates conversion R(0) and T(0) according to the index points.2. Compute the data $\{m_i \mid i=1, 2, L, N_p\}$ under the angel of view P and then determine the closest distance point $m_i'(k)$ under the angel of view Q. According to the efficient points criterion, determine whether m_i and$m_i'(k)$ are efficient corresponding points and further extract the corresponding points sets $\{m_i \mid i= 1,2,L ,N_k\}$,$\{ m_i'(k) \mid i= 1, 2,L ,N_k\}$, $N_k \le N_p$ of the overlapped part of visual angel P and Q.3. Eliminate the incorrect corresponding points couple based on the orthogonal Grey code, which is: if the orthogonal Grey codes of two corresponding points have one stripe difference in the horizontal or the vertical direction, then it is determined that the corresponding points are incorrect. 4. Solve the coordinates conversion R(k) and T(k) according to the acquired two points sets $\{m_i \mid i= 1,2,L ,N_k\}$, $\{m_i'(k) \mid i=1,2,L,N_k\}$.5.Compute the objective function $E(k) = \sum_{i=1}^{Nk} \left\| m_i^{'}(k) - \left[R(k)m_i + T(k)\right] \right\|^2$.6. If

$E(k\text{-}1)\text{-}E(k) \geq \varepsilon$ (ε is the given convergence precision), k=k+1. Then, go to step 2. If $0 \leq E(k\text{-}1)\text{-}E(k) < \varepsilon$, record R(k) and T(k) and the program ends.

4. Registration Experiment

As for the experimental data, we can evaluate the registration result according to the contact ratio of the index points after the coordinates conversion. Here, we define the contact error:

$$\varepsilon = \sum_{i=1}^{n} \left\| p_i - \tilde{p}_i \right\|^2 \qquad (6)$$

In the equation, P_i represents the root sum square of the 3D coordinates of the index points in the reference coordinate system and $\tilde{p}_i$ represents the root sum square of the 3D coordinates of the corresponding index points after the coordinate transition to the reference coordinate system.

4.1. The Simulated Experiment

Use 3dmax to establish the simulated measuring system, registration target *etc.*, and we can carry out the 3D measurement and the registration experiment. First of all, we set the index points with the surface method, the global camera method and the hexahedron targets method, respectively; then, use the quaternion method to achieve the preliminary registration and the accurate registration is with ICP method; finally, we compare the accuracy of the three methods.

Here, we set 5 index points on the surface of the measured piece as the evaluation points. We evaluate the registration accuracy according to the contact ratio of the index points from different visual angles.

Data in Table 1 are the measured coordinates of 3 index points in two different visual angles. In the simulating environment, the standard coordinates of an arbitrary point are known. We use the measured and the standard coordinates respectively to compute the conversion matrix so that we can evaluate the result with and without the measurement error included in the registration error.

Table 1. Measured Coordinates of Index Points (mm)

Index points	Visual angle1			Visual angle2		
	X	Y	Z	X	Y	Z
1	598.815	110.304	72.115	-258.758	-52.738	234.453
2	238.386	150.271	0.000	314.912	188.838	-27.892
3	300.158	600.570	-58.665	-258.543	775.458	15.458

Based on the conversion matrix, we can compute the contact errors of the 5 index points, which are shown in Table 2 and Tale 3.

Table 2. Contact Errors based on Measured Points (mm)

	1	2	3	4	5
The Surface Method	0.034	0.033	0.033	0.038	0.035
The Global Camera Method	0.035	0.033	0.035	0.039	0.037
The Hexahedron Targets Method	0.033	0.033	0.035	0.037	0.036

Table 3. Contact Errors based on Standard Points (mm)

	1	2	3	4	5
The Surface Method	0.016	0.015	0.018	0.018	0.011
The Global Camera Method	0.019	0.017	0.022	0.019	0.016
The Hexahedron Targets Method	0.017	0.016	0.019	0.019	0.016

We can get from the results of the experiment that: 1)the accuracy of the hexahedron targets method is a little bit lower than that of the surface method, which verifies the theoretical analysis; 2)the registration error is close to but a little bit higher than the measurement error in the simulating environment, which is to say, the registration error is mainly caused by the measurement, especially by the location error of the index points; 3)the simulating environment lacks the factors that cause the error, and therefore the ICP method does not show obvious advantage. Even if we only use the quaternion method, the registration accuracy is almost the same with the method that combines the ICP and quaternion method. The advantage of the ICP method is using multiple points fitting to further homogenize the registration error. However, there is no incorrect registration under the simulating environment. Using multiply points fitting otherwise introduces other errors, which decreases the registration accuracy and that does not agree with the reality.

4.2. The Actual Experiment

The process of the actual experiment is the same with the simulated experiment and in Table 4, we present the contact error of the 5 index points.

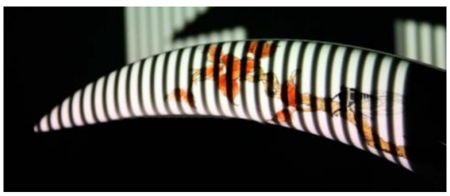
Table 4. Contact Errors (mm)

	1	2	3	4	5
The Surface Method	0.82	0.80	0.79	0.81	0.80
The Global Camera Method	0.85	0.84	0.83	0.88	0.85
The Hexahedron Targets Method	0.85	0.85	0.82	0.85	0.84

The measurement error is relatively large and it is the main factor of the registration error (the registration errors of the 3 methods are all close to the monocular measurement error), thus the registration accuracy of the hexahedron targets method is a little lower than the surface method, but it is not obvious.

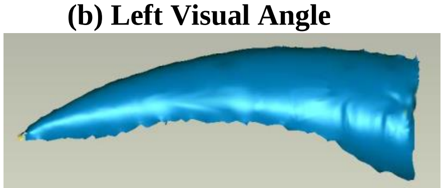
The registration experiment on complex surface is shown in Figure 3. The object shown in Figure 3(a) is a ceramic ivory. It needs to be partially measured because it is too long for a one-time measurement; Figure 3(b) and Figure 3(c) shows the coded images in two visual angels, which reflect different measured parts; The reconstruction result from two visual angels are shown in Figure 3(d) and Figure 3(e); at last, the registration result is presented in Figure 3(f). From the figure we can see that the registration has a good visual effect and reconstructs the details of the measured surface integrally and actually.

(a) Ceramic Ivory

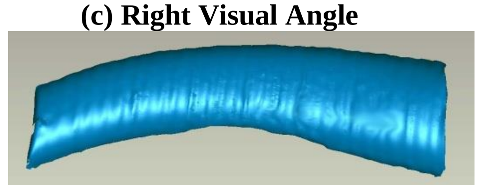


(b) Left Visual Angle

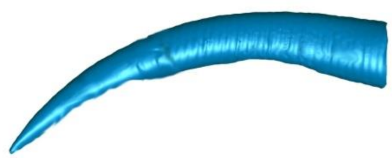
(c) Right Visual Angle



(d) Reconstruction from the Left Visual Angle



(e) Reconstruction from the Right Visual Angle



(f) Registration

Figure 3. Registration of Complex Surface

5. Conclusion

In this paper, we propose the principle of the hexahedron targets registration method. First, we set the index points couple and achieve the preliminary registration with the quaternion method, which solves the problem that the index points cannot be set on the measured surface and ensures the registration accuracy without the addition of other apparatus. Furthermore, we achieve the accurate registration with the ICP method. During the accurate registration, we develop a technique based on orthogonal edging Grey code to eliminate the incorrect point couples, which improve the iterative convergence.

According to the result of the simulated registration experiment, the registration error of the proposed method is about 0.03mm, which is close to the surface method and the global camera method. Besides, from the actual registration experiment, we can see that the registration error of the proposed method is about 0.8mm, which is close to the global camera method and a little bit higher than the surface method. Finally, the registration of the complex surface has a good visual effect and reconstructs the details of the measured surface integrally and actually. Due to the surface features of metals and ceramics, the proposed method has a huge advantage in applications.

Acknowledgements

The article studies by Technical Innovation Talents Research Foundation of Harbin (2013RFQXJ090), Postdoctoral Scientific Research Foundation of Heilongjiang Province (LBH-Q12069), Youth Top-notch Innovative Talents Training Program of Harbin University of Science and Technology, National Natural Science Foundation of China (61005035).

References

[1] F. Philipp and E. Peter, "Adaptive color classification for structured light systems [C]", IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops, **(2008)**: 4563048.
[2] G. H. Xie, J. H. Sun and Z. Yang, "3D Data Registration Method for Vision Measurement", Journal of Beijing University of Aeronautics and Astronautics, vol. 7, **(2009)** , pp. 877-881.
[3] T. Q. Ren, "The Study on High-accuracy Mosaic for Large 3D Free-form Measurement", Tianjin University, **(2008)**.
[4] H. B. Wu and X. Y. Yu, "Structured Light Encoding Stripe Edge Detection Based on Grey Curve Intersecting Point", Acta Optica Sinica, vol. 8, no. 6, **(2008)**, pp. 1085-1090.
[5] P. Mountney, D. Stoyanov and G. Z. Yang, "Three-dimensional tissue deformation recovery and tracking [J]", Signal Processing Magazine, IEEE, vol. 27, no. 4, **(2010)**, pp. 14-24.
[6] S. Roehl, S. Bodenstedt and S. Suwelack "Dense GPU-enhanced surface reconstruction from stereo endoscopic images for intraoperative registration", Medical physics, vol. 39, no. 3, **(2012)**, pp. 1632-1645.
[7] B. Amberg, S. Romdhani and T. Vetter, "Optimal step nonrigid icp algorithms for surface registration", Computer Vision and Pattern Recognition", (2007). CVPR'07. IEEE Conference on. IEEE, **(2007)**, pp. 1-8.
[8] J. Park, G. N. DeSouza and A. C. Kak, "Dual-beam structured-light scanning for 3-D object modeling, 3-D Digital Imaging and Modeling", Proceedings, Third International Conference on. IEEE, **(2001)**, pp. 65-72.
[9] Z. Z. Wang, L. L. Yu and A. K. Yang, "The research on the ICP algorithm based on the normal vector of the curved surface", Microcomputer Information, vol. 21, **(2010)**, pp. 145-147.
[10] C. Zuo, M. Lu and Z. G. Tan, "A Novel Algorithm for Registration of Point Clouds", Chinese Journal of Lasers, vol. 39, no. 12, **(2012)**, pp. 211-218.