Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

A Dual-SLS for Efficient 3D Scanning of Dynamic Objects*

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***Abstract* - Structured light-based 3D sensing techniques has been an important means for 3D digitization of real objects. However, to obtain a complete 3D model of target, multiple scans are demanded and that makes the operation time-consuming. In this paper, an efficient 3D scanning system is introduced, which is composed of two structured light sensors. The two sensors are placed in opposite directions, and the target is placed between them. With a single scan operation, two point clouds can be obtained and aligned by the proposed system calibration parameters. For some objects with relative simple geometry like human hands, a complete 3D model can be obtained via single scan. But regarding to complex targets, by changing the target orientation several times and using the proposed point cloud registration method, complete 3D model can be obtained more efficiently. Experiments with different objects are implemented to verify feasibility and accuracy of the proposed method.**

Index Terms - Structured light, 3D reconstruction, point cloud registration.

I. INTRODUCTION

3D reconstruction of real objects is an important research topic in computer vision domain with wide applications in 3D games, industrial inspection, virtual reality and robotics etc. Existing 3D reconstruction techniques includes stereo vision, structured light and Time of Flight [1, 2, 3]. Recent works in this domain mainly focused on real-time, high-resolution, omnidirectional and high-quality reconstruction. Among different 3D sensing techniques, structured light-based 3D scanning means is mostly researched and adopted for its high accuracy and efficiency. However, to obtain a complete 3D model of the targets, multiple scans are usually demanded, and that makes the operation more time-consuming. Accuracy of the 3D model is also affected by the alignment error of multiple scans.

To obtain a complete 3D model of a target, traditional single 3D sensor-based methods have to scan the target for different viewpoint and align different 3D point clouds together. Existing methods can be classified into two classes: Marked and unmarked methods. Scanning through one set of equipment, artificial markers are usually attached on the target surface manually before the operation. The tremendous amount of work is involved in sticking markers. Besides, many scanned surfaces like precious artifacts are not allowed to paste marker points [4, 5]. The difficulty of obtaining a full object model by multiple scans without marking the object is to register multiple point clouds together. There are two ways to solve the problem of unmarked registration of multiple scans: image-based registration and geometric-based registration. Image-based registration relies on the surface texture of the object to achieve registration, and objects with simple textures are not effective [6, 7]. Geometric-based registration is related to the geometrical characteristics of the object and is poorly stable when measuring geometrically simple or symmetrical objects [8, 9]. Most of the scanner systems available today use a turntable to rotate an object so as to capture images of the object from different viewpoints [10, 11, 12]. For these systems, the motion of the object is constrained to rotate around a fixed axis. As long as the rotation axis is calculated accurately with respect to the structured light coordinate system, the 3D registration issue can be greatly simplified. The problem is that the accuracy of the turntable is limited by the system cost, but the registration accuracy is inseparable from the turntable accuracy. Meanwhile, the occluded missing data cannot be obtained due to the limitation of the turntable. A novel registration method using two axis rotation turntables was proposed by [13]. The use of two set of turntables can increase the field of view, but this also does not complete the full object scan, and the error of the turntable calibration is further increased. One-shot imaging for measuring the shape of an object is proposed by [14], which presents a new system for acquiring complete 3D surface models using a single structured light projector, and a pair of planar mirrors, but unable to reconstruct high-precision models.

The most efficient solution to high-precision full-object reconstruction is to capture the geometry of the object using a multi-view camera system. These systems recover surface shape generated from camera view [15, 16, 17, 18, 19].

Using several projectors is one of the most convenient methods for Multiple systems reconstruction. However, it faces two problems, namely, the mutual interference of multi-channel devices and the relatively high reconstruction cost. To solve the two problems, Furukawa al.[15] has proposed an one-shot shape reconstruction method using a projector, projecting pattern that is easily decomposed and detected. PETKOVIĆ al. [16] proposed to use temporal phase-shifts to enable multiplex in fringe-projection profilometry for efficient separation

* This work was supported in part by the National Key R&D Program of China (No. 2017YFB1103602), Shenzhen Science Plan (KQJSCX20170731165108047, JCYJ20170413152535587), and the National Natural Science Foundation of China (U1613213, U1713213).

between projected sinusoidal fringe patterns. Yan al.[20] proposed a multi-projector system that combines De Bruijn color sequences and random dot patterns.

In this paper, we present a unmarked SLS(structured light system) consisting of two sets of structured-light subsystems to capture the geometry of a subject from surrounding views. Industrial cameras take high-quality pictures up to 170 frames, and it takes only 200ms for two sets of devices to acquire a set of pictures. In this 3D scanner system, the encoded pattern depicted in [21] was used to measure the 3D pieces and the corresponding relations between pixels in the images and points in the point cloud. The pending crucial issue is to capture a full object accurately and automatically using only two sets of equipment. The registration of the point cloud generated by the two sets of equipment can be easily solved by solving the rotational translation matrix with the calibration plate we designed. With a simple analysis of the system, we can find that, the geometric relationship between the two systems that can be used as a coarse registration constraint. According to the constraint condition, using fast-ICP algorithm complete automatic registration of two objects with different spatial positions with no need to mark on the object to complete scanning [22].

The paper is organized as follows. Section II presents the algorithm details and procedures. In Section III, experimental results and evaluation are showed and discussed to verify the proposed method. Finally, the conclusion and future work are presented in Section IV.

II. THE METHODOLOGY

In order to complete a full object reconstruction, multiple views of the object must be obtained.

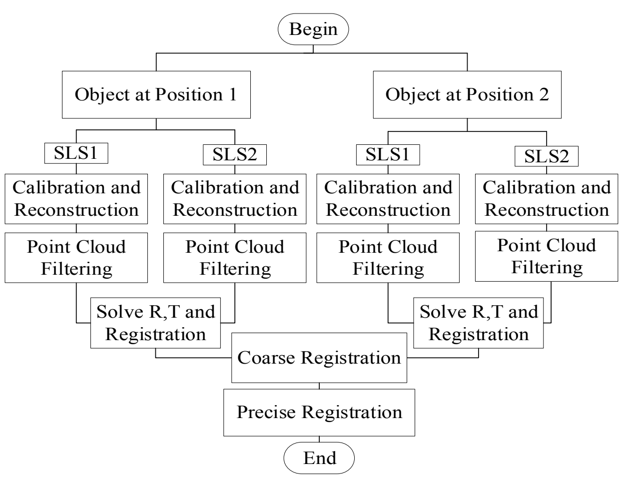


Fig. 1. Algorithm flow.

Rotating and panning an object is equivalent to building a virtual camera to get complete 3D information. Using real and virtual camera, we then recover a dense 3D point cloud by multiple registrations. The main Algorithm flow of the system is shown in Fig. 1.

A. Calibration Between Two Sets of SLS

To complete a 360-degree object reconstruction with minimal equipment, it is necessary to use the scanning system with a unique design. The designed structure is demonstrated in Fig. 2.

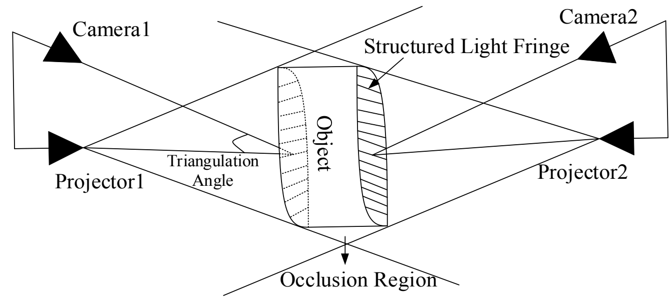


Fig.2. Schematic diagram of the system.

Over the years, many algorithms have been proposed to calibrate projector-camera systems [23, 24]. For our system, we follow the mature method of using a calibrated camera to subsequently the intrinsic and extrinsic parameters of the projector are calculated. Calibration between the two systems is the crux of the matter since the two systems have no overlapping fields of view. The relations between 3D point cloud and pixels in the 2D image can be known because of the structured light technique. We have designed a very thin calibration plate used accurate calibration of R(Rotation matrix) and T(Translation Matrix) between two sets of equipment. It is noted that the double-sided chessboard corner locations in the world coordinate system are just the same. The structured light pattern is projected on the checkerboard, and the checkerboard target 3D model can be recovered by the traditionally structured light algorithms. The corner points detection algorithm can be used to find the pixel coordinates of the checkerboard corner point, and the joint equation can be easily solved to obtain several sets of 3D point pairs under two sets of equipment. Find the R, T that minimizes the error with Least Square analysis method. The mathematical models are summarized as (1). Where γ is a function solved by Zhang's method [25].

$$\min_{R,t} error = \min_{R,t}\left(\frac{1}{2}\sum_{i=1}^{n}\left\|\gamma(u_i,v_i)-R\gamma(u_i,v_i)+T\right\|_2^2\right) \quad (1)$$

B. Registration and Obtain Complete Model

After the calibrating step, the three-dimensional model of the object was basically recovered and by using Poisson fusion algorithm the occluded region is packed with appropriate texture and then generate a fully closed 3D model. Due to the occlusion issue, some important textures are inevitably lost [26]. The unreliability of the surface texture is not permitted for some applications such as industrial inspection, medical measurement and so on. We propose an innovative registration method for elimination of occlusion for the more real model.

The registration of two point clouds is to find the rotation matrix and translation matrix between them. Next, we will gradually describe the method of finding the rotation and translation matrix according to the characteristics of our system. Acquiring multiple views of an object by rotating and panning the object is equivalent to rotating and translating the device. That is, multiple virtual structured optical devices are produced. From the perspective of the device, it is easier to dig out some of the hidden geometric relationships. Using real and virtual device, we then recover a dense 3D point cloud spanning the entire object surface if we find registration conditions. The real and the virtual device formed by rotating the object are shown in Fig. 3.

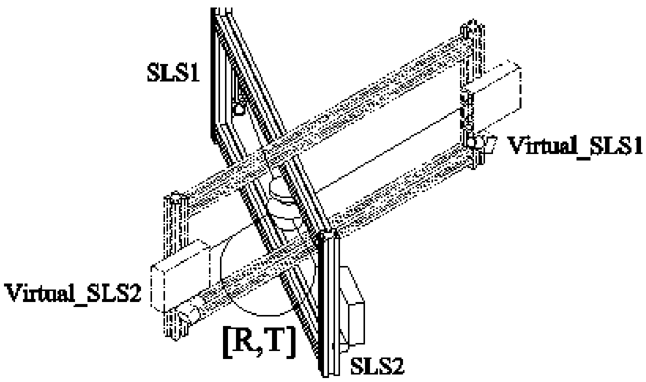


Fig. 3. Illustration of the structured light system.

The first step, we focus on the coordinate relationship which is decided by two projectors optical centers as illustrated by Fig. 4. Pro1_plane is filtered point clouds reconstructed by the pro1. M1 is a point in the Pro1_plane. M1 is the point under the coordinate system of $O_{pro1}X_{pro1}Y_{pro1}Z_{Pro1}$. Due to the symmetry of the device, the same is true for pro2. The distance between the O_{pro1} and O_{pro2} can be calculated as:

$$L = \left| O_{PRO1}R + T - O_{PRO2} \right| \tag{2}$$

Convert the pro2 coordinates system to the pro1 coordinate system. Assuming that $M_{2i}(x_{2i}, y_{2i}, z_{2i})$ is any point in pro2_plane, then converting to the pro1 coordinate system can be expressed as:

$$M'_{2i} = M_{2i}R + T \tag{3}$$

Assuming that $M_{1i}(x_{1i}, y_{1i}, z_{1i})$ is any point in pro1_plane. The average distance between the two planes can be expressed as:

$$d = \left| \sum_{i=1}^{n} \frac{x_{2i}}{n} - \sum_{j=1}^{m} \frac{x_{1j}}{m} \right| \tag{4}$$

Objects can be moved to the center of the system by the following formula, regardless of where the object is located in the system.

$$D = \frac{L-d}{2} \tag{5}$$

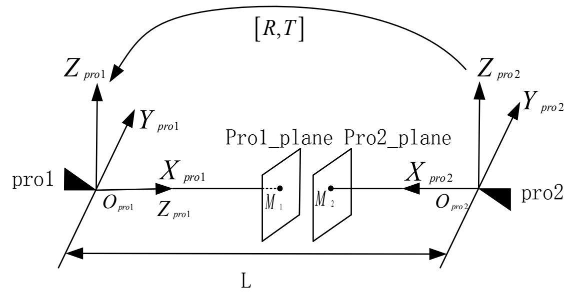


Fig.4. Illustration of the geometric relation.

The next step requires estimating the rotation matrix. The solution of the rotation matrix is not too difficult since the model we obtained earlier is a complete model after Poisson fusion. It is easy to get the center of gravity of the model using the algorithm in PCL(Point Cloud Library). As long as the shape of the reconstructed object does not change greatly, the center of gravity of the object will nearly not change. Since the final need to use the ICP (Iterative Closest Point) registration algorithm for accurate registration, the error will not affect final result [27]. Using ICP and the center of gravity, traversing point can find the point that is farthest from the center of gravity and the nearest point, and projecting to a 2D image to find a matching point for another point cloud. Based on three points, the rotation matrix between the two point clouds can be estimated. The solution diagram is shown in Fig. 5.

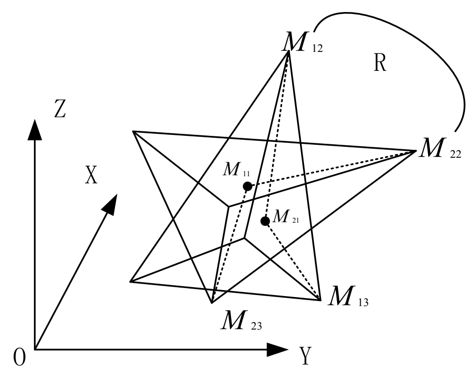


Fig.5. Illustration the solution of Rotation matrix.

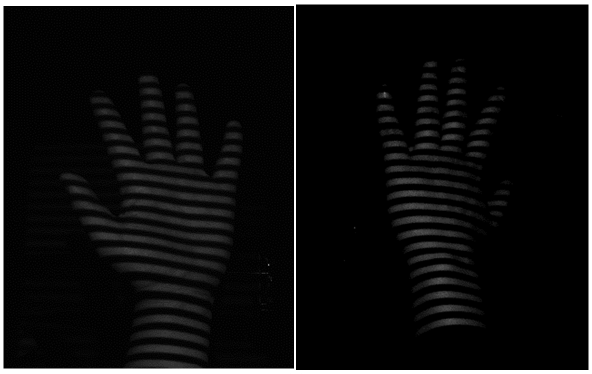
Through preliminary calculation of the rotation and translation matrix, using fewer points for iterative calculation, using the fast ICP algorithm to achieve accurate registration of point clouds data.

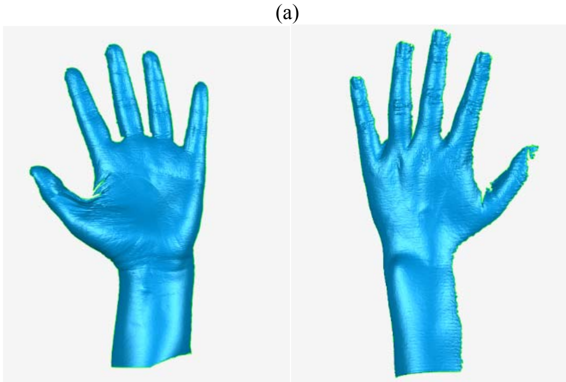
III. Experiment Results And Analysis

A. *Experiment setup and results*

To verify the results of the proposed method, two sets of SLS are fixed on both sides of the bracket as shown in Fig. 6. Using structured light technique to create hand model, a non-rigid objects, verified the advantages of the algorithm. The target and its point cloud in our system is shown in Fig. 7. To evaluate the registration results, the previous result is used in the experiment. The reconstructed 3D model is as displayed at various viewpoints as shown by Fig. 8. From the results, we can see registered precisely via the proposed method.

Fig. 6. The experimental setup.


(a)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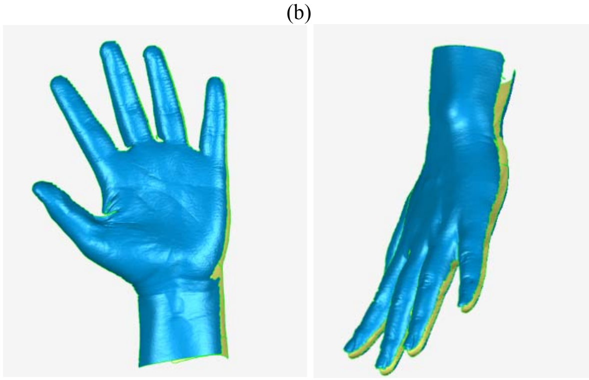
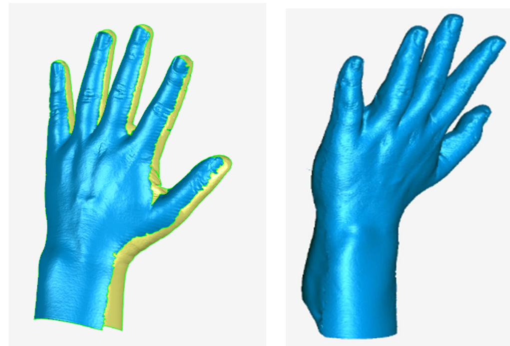

(c)

Fig 7. Results of calibration:(a) Targets to be reconstructed; (b) Single point cloud of hand after fusion;(c) Point cloud after registration and fusion.

B. Evaluation and discussion

Our method has been applied to objects such as hands with relatively simple geometry. In this section, the results show the effectiveness of the method and its adaptation capacity to different environments. Figs. 9–10 shows some of the complicate targets to evaluate the proposal. Figure shows point clouds from different viewpoints, and the final generated mesh by the Poisson algorithm.


(a)

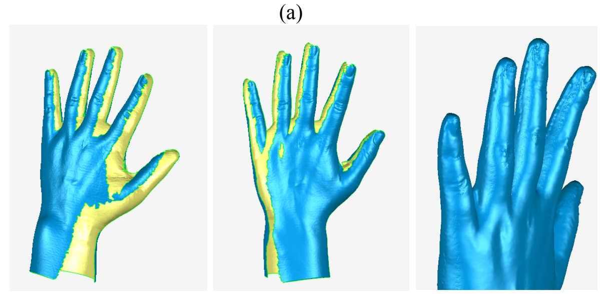
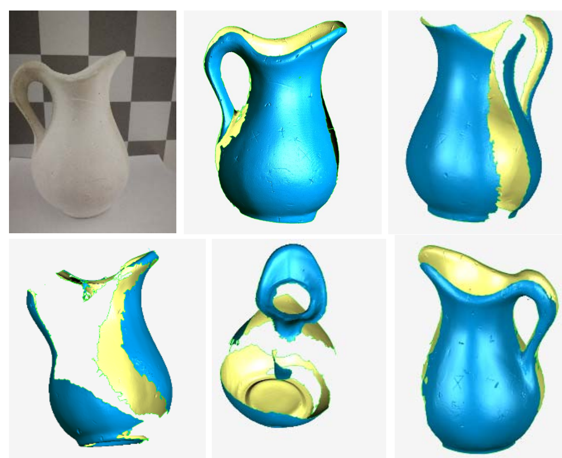

(b)

Fig.8. For some objects with relatively simple geometry like human hands, a complete 3D model can be obtained via single scan. (a) Hand model acquired in single scan, generated mesh from the Poisson algorithm and local details are lost;(b) Complete model acquired after multiple scans and defects of multiple scan reconstruction of non-rigid objects.


(a)

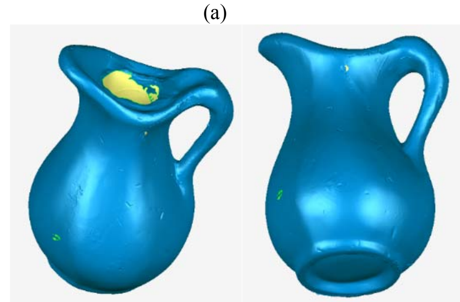

(b)

Fig.9. Example of kettle model reconstruction process, which is a symmetrical rigid object with few surface features: (a) Five viewpoints of the obtained reconstruction; (b)The full-object generated mesh from the Poisson algorithm.

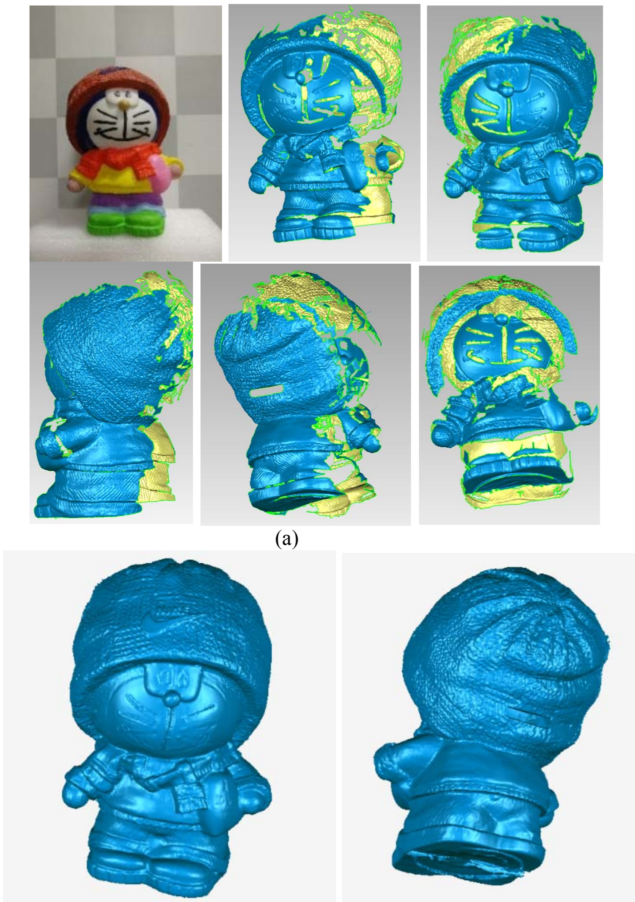


Fig.10. Reconstruction process of objects with rich surface texture feature: (a) Five viewpoints of the obtained reconstruction; (b)The full-object generated mesh from the Poisson algorithm.

These results confirm that this full object Scanning reconstruction method is feasible and valid. No matter how complicated the shape of object, our equipment can achieve accurate reconstruction results with very few scans. However, one problem is the reconstruction of non-rigid objects, which cannot complete full object scanning due to the field of view limitations. This is a limitation we would like to address in future work.

IV. Conclusion And Future Work

This paper presents a new method for full object scanning based on dual-set structured light systems. After the calibration system and point cloud registration, a complete 3D model can be obtained. Experiments confirm the reconstruction effect, for rigid objects, a complete high-quality point cloud can be obtained. It takes only about 200ms to get a set of data. Non-rigid problems also have good results in some situations. But the reconstruction of non-rigid is still an urgent problem to be solved. Reconstruction with better accuracy, speed, and robustness are needed to realize in the future.

References

[1] F. Gu, H. Zhao, Zhan. Song, "A simple method to achieve full-field and real-scale reconstruction using a movable stereo rig," *Measurement Science and Technology*, vol. 29, no. 6, 2018.

[2] Shulan. Huang, Feifei. Gu, Zhiquan. Cheng, Zhan. Song, "A Joint Calibration Method for the 3D Sensing System Composed with ToF and Stereo Camera," *IEEE International Conference on Information and Automation*, 2018.

[3] Y. Chen, Z. Song, S. Lin, "Capture of hair geometry using white structured light," *Computer-Aided Design*, vol. 96, pp. 31-41, 2018.

[4] Kim, Seo, Lee, "Simultaneous registration of multiple views with markers," *Computer-Aided Design*, vol. 41, no. 4, pp. 231-239, 2009.

[5] Barone S, Paoli A, Razionale A, "Three-dimensional point cloud alignment detecting fiducial markers by structured light stereo imaging," *Machine Vision and Applications*, vol. 23, pp. 217-229, 2012.

[6] Johnson A E, Hebert M, "Using spin images for efficient object recognition in cluttered 3D scenes," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 21, pp. 443-449, 2002.

[7] J. Zhu, S. Xu, Z. Jiang, "Multi-view registration of unordered range scans by fast correspondence propagation of multi-scale descriptors," *PLoS ONE*, 13(9), 2018.

[8] Kleppe A L, Egeland OA, "Curvature-Based Descriptor for Point Cloud Alignment Using Conformal Geometric Algebra," *Advances in Applied Clifford Algebras*, vol. 28, 2018.

[9] Cao W, Lyu F, He Z, "Multi-modal medical image registration based on feature spheres in geometric algebra," *IEEE Access*, pp. 1-1, 2018.

[10] Y. Ye, Zhan. Song, "An accurate 3D point cloud registration approach for the turntable-based 3D scanning system," *International Conference on Information & Automation*, pp. 982-986, 2015.

[11] Bojian W, Yang Z, Yiming Q, "Full 3D reconstruction of transparent objects," *ACM Transactions on Graphics*, vol. 37, pp. 1-11, 2018.

[12] Li D, Zhang H, Zhan S, "An automatic laser scanning system for accurate 3D reconstruction of indoor scenes," *IEEE International Conference on Information & Automation*, 2017.

[13] D. He, X. Liu, Z. Cai, "An automatic registration system of multi-view 3D measurement data using two-axis turntables," *SPIE Optical Engineering + Applications. Applications of Digital Image Processing*, 2016.

[14] Ryo Furukawa, Ryusuke Sagawa, Hiroshi Kawasaki, "One-shot Entire Shape Acquisition Method Using Multiple Projectors and Cameras," *2010 Fourth Pacific-Rim Symposium on Image and Video Technology*, pp. 107-114, Nov 2010.

[15] T Petkovi, Tomislav Pribanic, Matea Donlic, Nicola Dapuzzo, "Multi-Projector Multi-Camera Structured Light 3D Body Scanner," *Proceedings of 3DBODY. TECH*, pp. 11-12, 2017.

[16] T Petkovic,Tomislav Pribanic, Matea Donlic, Peter F Sturm ,"Efficient Separation Between Projected Patterns for Multiple Projector 3D People Scanning," *International Conference on Computer Vision*, pp. 815-823, 2017.

[17] Stuart Woolford, Ian S Burnett, "Toward a one-shot multi-projector profilometry system for full field of view object measurement," *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp.569-573, 2014.

[18] Hassan Afzal, Djamila Aouada, Bruno Mirbach, Björn Ottersten, "Full 3D Reconstruction of Non-Rigidly Deforming Objects", *ACM Transactions on Multimedia Computing, Communications, and Applications*, vol. 14, pp. 1, 2018.

[19] Lanman D, Crispell D, Taubin G, "Surround Structured Lighting for Full Object Scanning," *International Conference on 3-d Digital Imaging & Modeling,* pp.107-116, 2007.

[20] Z. Yan, L. Yu, Y. Yang, and Q. Liu, "Beyond the interference problem: hierarchical patterns for multiple-projector structured light system," *Applied Optics*, vol. 53, pp. 3621-3632, 2014.

[21] Z .Song, R. Chung, XT. Zhang, "An accurate and robust strip-edge based structured light means for shiny surface micro-measurement in 3D," *IEEE Transactions on Industrial Electronics*, vol. 60, pp. 1023-1032, 2013.

[22] Pomerleau F, Magnenat S, Colas F, "Tracking a depth camera: Parameter exploration for fast ICP," *International Conference on Intelligent Robots & Systems*, 2011.

[23] Y. Song, Z. Song, S. Wu, "Calibration Methods of Projector-Camera Structured Light System: A Comparative Analysis," *International Conference on Intelligent Autonomous Systems*, pp. 39-43, 2018.

[24] Y. Ye, Z. Song, "A Practical Means for the Optimization of Structured Light System Calibration Parameters," *International Conference on Image Processing*, pp. 1190-1194, 2016.

[25] Z. Zhang, "A flexible new technique for camera calibration," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 22, no. 11, pp. 1330-1334, Nov 2000.

[26] Stulp F, Dell'Acqua F, Fisher R, "Reconstruction of surfaces behind occlusions in range images," *Proceedings Third International Conference on 3-D Digital Imaging and Modeling*, pp. 232-239, 2001.

[27] Maris M, Fiorini P, "Generalized Shapes and Point Sets Correspondence and Registration," *Journal of Mathematical Imaging and Vision*, vol. 52, no. 2, pp. 218-233, 2015.