Digital Template System for Measuring Turbine Blade Forging and Its Calibration Method

Yongkai Cai[1,2], Xu Zhang[1,2](✉), Zelong Zheng[2], Limin Zhu[3], and Yuke Zhu[2,3]

[1] School of Mechatronic Engineering and Automation, Shanghai University, No. 99 Shangda Road, BaoShan District, Shanghai 200444, China
xuzhang@shu.edu.cn

[2] HUST-Wuxi Research Institute, No. 329 YanXin Road, Huishan District, Wuxi 214100, China

[3] Robotics Institute, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Minhang District, Shanghai 200240, China

Abstract. Because of complex profile and large size, the measurement of turbine blade is complicated and difficult. A digital template measurement system is developed, which is composed of two laser scanners, two linear motion modules, one turntable and the developed blade measure & analysis software. In order to achieve high precision, the specific calibration method is proposed for each part, such as the laser scanner, the motion direction of scanners, the relative pose between scanners, and the axis of the rotation module. In the first and second calibration stage, only the calibration board is adopted. After the camera is calibrated, the laser plane and the motion direction of scanner are determined with PnP method. In the third and fourth calibration state, the sphere is adopted as the feature to determine the parameters. In the experimental section, we analyze the precision of calibrated system and introduce the application of blade measurement.

Keywords: Calibration · Laser scanner · Turbine blade measurement

1 Introduction

As one of the most important parts of turbine machinery, turbine blade has complex profile, large size span and numerous description parameters. Its profile quality directly affects the energy conversion efficiency, so blade detection becomes a significant link in blade manufacturing. In addition, because of the large number and size of blade, high demands are placed on measurement efficiency and accuracy.

The contact measurement method includes standard template method and coordinate measurement machine(CMM). The accuracy of the standard template method is low because it depends too much on operators experience. Although CMM is widely used to measure complex surface, it not only has

Z. Chen et al. (Eds.): ICIRA 2018, LNAI 10984, pp. 342–353, 2018.
https://doi.org/10.1007/978-3-319-97586-3_31

low efficiency for the point-by-point measurement of blade profile and pattern, but also requires complex path planning for the object and probe radius compensation.

Non-contact measurement methods include optical theodolite, stereo photography, laser interferometry and laser triangulation method [1]. Fu et al. [2] proposed a method to measure the blade profile by structured light which expands the blade phase rapidly with a new coding method. But the stripe pattern is not suitable for low exposure situations. Sun et al. [3–5] designed a non-contact measurement system with four axis which can only measure the aero-engine blades with height less than 0.36 m.

Aiming at the efficient measurement and result analysis of turbine blades with height less than 1 m, we design the digital template measurement system based on line laser triangulation. In this system, one-dimensional motion module is used to make the laser scanner quickly reconstruct the blade profile, the complete point cloud of the blade is obtained by the rotation of turntable, and customized measurement report is exported automatically. According to the system model, it requires to calibrate the laser scanner, motion direction, relative pose between scanners and turntable coordinate system. The calibration of laser scanner is to solve the relative pose of laser plane and camera, and the main methods are mechanical adjustment method [6,7], drawing calibration method [8,9], invariance of cross-ratio method [10–12] and so on. The calibration of rotation axis of turntable is to obtain the rotation center and the direction of rotation axis, mainly divided into calibration object method [13–16] and no calibration object method [17].

In the above-mentioned measurement methods, contact measurement is inefficient, while non-contact measurement is designed for small blades. Each of the mentioned calibration methods is only applicable to specific conditions, and the calibration objects are different. According to the characteristics of digital template system, our calibration method unifies the calibration objects of each calibration link, simplifies the overall calibration process and improve the efficiency of system calibration.

This paper presents a complete calibration method of digital template measurement system for turbine blade forging. We establish the system coordinate frame and provide the transformation relationship and calibration method between each coordinate system. In the experimental part, the reconstruction accuracy of the calibrated measurement system is analyzed in detail. Finally, we also show the applications of the calibrated system in the actual blade measurement tasks.

2 Digital Template Measurement System

The measurement system consists of two vision scanners, two high-precision linear modules, turntable, working platform and control cabinet. The turbine blade should be fixed with a fixture vertically to the turntable before the measurement. Each linear module loads a vision scanner for vertical motion, and turntable rotates the blade.

As illustrated in Fig. 1, the blade measurement system requires to establish the coordinate system of camera, laser plane, measurement and turntable. The origin of the camera coordinate system is the optical center of camera, the direction of the optical axis of camera is taken as the direction of Z_c axis, the Y_c axis is on the plane where laser projector and camera are located and perpendicular to the Z_c axis, and the direction of X_c axis is the direction of the multiplication cross result of their unit vectors. The origin of the laser plane coordinate system is the vertical foot from the camera optical center to the laser plane, the direction of Z_l axis is the projection direction of the camera optical axis on the laser plane, the direction perpendicular to Z_l axis and passing through the origin is taken as Y_l axis, and the direction of X_l axis is the direction of multiplication cross of both unit vectors. The origin of the measurement coordinate system is the pulse zero point of the linear module, the direction of Y_m axis is the actual movement direction of scanner, the direction of Z_m axis is the projection direction of Z_l axis perpendicular to Y_m axis in the laser plane coordinate system, and X_m axis is created by right hand coordinate system. The origin of the turntable coordinate system is established in the center of turntable, the plane normal direction of turntable is taken as the direction of Z_t axis, the direction of X_t axis is the direction of multiplication cross of unit vectors of camera optical axis and Z_t axis, and Y_t is also established by right hand coordinate system.

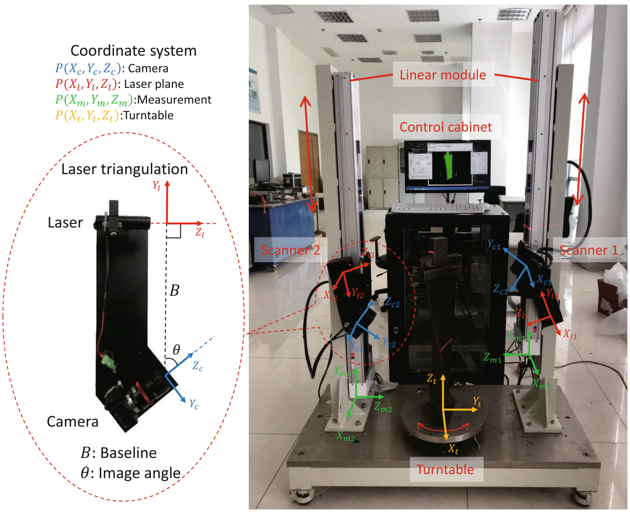

Fig. 1. System structure and coordinate system model

After taking laser images by camera, we convert the coordinates of the extracted laser stripe points from the camera coordinate system to the laser plane coordinate system. Due to the calibration of motion direction, these points can be transformed into the measurement coordinate system. Finishing the transformation of point cloud reconstructed by Scanner 2 to the measurement coordinate system of Scanner 1, we can unify all measuring results into the turntable coordinate system so that the complete point cloud can be obtained.

3 Calibration Method

The whole system calibration process is divided into four calibrations of laser scanner, motion direction, relative pose between scanners and turntable coordinate system. The first two parts only needs a general planar calibration board, and the other two will use a criterion sphere.

3.1 Calibration of Laser Scanner

We adopt an iterative method based on ring characteristic pattern to calibrate the camera. After taking pictures of the calibration board under different poses in the view field of the camera, we can obtain the interior and exterior parameters of the camera according to the calibration method of Zhang [18]. Then we convert the original image into a view parallel to the calibration plate to extract the center of the ring and map the ring center points to three-dimensional planar points. The last step is mapping three-dimensional points of the ring centers to the original image to get corresponding information. Repeat the above process and the convergence is judged by whether the direction projection error is reduced or the number of iterations is maximum.

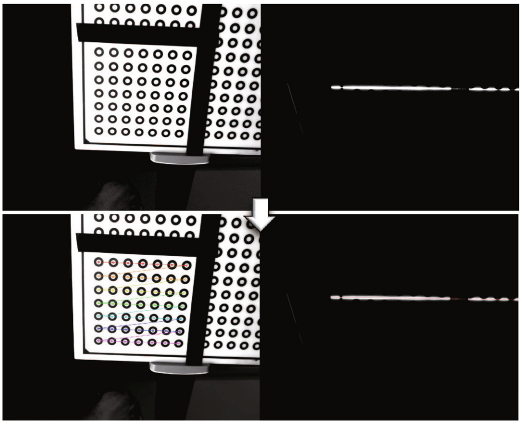

Fig. 2. Ring detection and laser stripe center extraction

As is shown in Fig. 2, laser plane is calibrated by taking multiple sets of calibration board images with and without laser. The specific process comprises the following steps: firstly, take a calibration board without laser and keep the calibration board still. Then turn on the laser and reduce the exposure. Finally, take a calibration board image with laser in the same pose. The poses of the calibration board in the camera coordinate system are obtained from the images without laser by PnP method [19], and the laser stripe center is extracted from the pictures with laser. Since y_l of the laser stripe center is 0, the transformation of the laser stripe center between the image coordinate system and the laser plane coordinate system can be expressed as:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha_u & 0 & u_o \\ 0 & \alpha_v & v_o \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_1 \; r_3 \; t \end{bmatrix} \begin{bmatrix} x_l \\ z_l \\ 1 \end{bmatrix} = H \begin{bmatrix} x_l \\ z_l \\ 1 \end{bmatrix} \tag{1}$$

where r_i is the i column vector of rotation matrix, α_u and α_v are the scale factors on the axis u and axis v of the image coordinate system, (u_o, v_o) is the coordinate of principal point, H is the scanner parameter matrix.

Finally, we fit laser plane in the camera coordinate system by least square method.

3.2 Motion Direction

Due to the error of installation and mechanical structure, we must calibrate the vector of motion direction in the camera coordinate system, which is namely the Y axis of the measurement coordinate system.

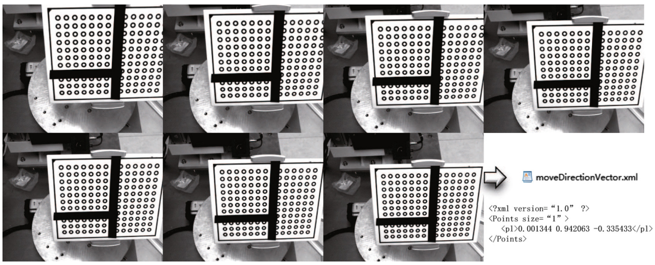

Fig. 3. Calibration images of motion direction and vector

As is shown in Fig. 3, the motion direction calibration is to fix the calibration board in the measurement space and make the linear module carry the scanner to move a plurality of positions to take photos of the calibration plate. We use PnP method to calculate the pose of the calibration board relative to the camera, fit the straight line of each pose, and obtain the vector of the motion direction in the camera coordinate system. The conversion of the laser stripe center coordinate from the laser plane coordinate system to the measurement coordinate system can be described as:

$$\begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix} = {}^{m}R_l \begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} + Y_m = {}^{m}R_l \begin{bmatrix} x_l \\ 0 \\ z_l \end{bmatrix} + \begin{bmatrix} 0 \\ P_n \cdot P_s \\ 0 \end{bmatrix} \tag{2}$$

where ${}^{m}R_{l}$ is rotation matrix from the laser plane coordinate system to the measurement coordinate system, P_n and P_s are the number of input pulses and the physical distance corresponding to a unit pulse for linear module motion.

So when the scanner moves H_c in the camera coordinate system, the transformation of laser plane coordinate system and measurement coordinate system can be expressed as:

$$ {}^{m}T_{c} = \begin{bmatrix} E & Y_m H_c \\ 0 & 1 \end{bmatrix} {}^{l}T_{c} \tag{3} $$

where m and l represent the coordinate system of measurement and laser plane.

3.3 Relative Pose Between Scanners

As is shown in Fig. 4, the relative pose between scanners calibration is to reconstruct the criterion sphere in multiple positions with two scanners in the same time. After fitting point cloud of both scanners into spheres, we obtain the spherical center coordinates and the correspondence between two sets of spatial points. Firstly, calculate the centers of gravity of two sets of points:

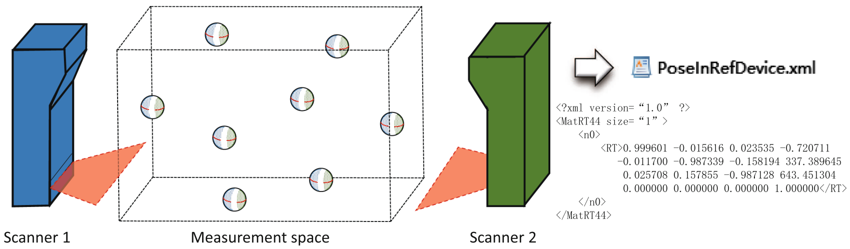

Fig. 4. Calibration of relative pose between scanners and transformation matrix

$$ \begin{aligned} \begin{bmatrix} x_{ag} & y_{ag} & z_{ag} \end{bmatrix}^T &= \frac{1}{n} \begin{bmatrix} \sum_{i=1}^{n} x_{ai} & \sum_{i=1}^{n} y_{ai} & \sum_{i=1}^{n} z_{ai} \end{bmatrix}^T \\ \begin{bmatrix} x_{bg} & y_{bg} & z_{bg} \end{bmatrix}^T &= \frac{1}{n} \begin{bmatrix} \sum_{i=1}^{n} x_{bi} & \sum_{i=1}^{n} y_{bi} & \sum_{i=1}^{n} z_{bi} \end{bmatrix}^T \end{aligned} \tag{4} $$

where a, b represent Scanner 1 and Scanner 2, $n(n \geq 3)$ is the number of points, $(x_{ai}\ y_{ai}\ z_{ai})(i = 1, 2, \ldots, n)$ and $(x_{bi}\ y_{bi}\ z_{bi})(i = 1, 2, \ldots, n)$ are points from Scanner 1 and Scanner 2.

Then rotation matrix ${}^{a}R_{b}$ of Scanner 2 relative to Scanner 1 can be calculated by

$$ \begin{bmatrix} x_{a1} & y_{a1} & z_{a1} \\ x_{a2} & y_{a2} & z_{a2} \\ & \vdots & \\ x_{an} & y_{an} & z_{an} \end{bmatrix} = {}^{a}R_{b} \begin{bmatrix} x_{b1} & y_{b1} & z_{b1} \\ x_{b2} & y_{b2} & z_{b2} \\ & \vdots & \\ x_{bn} & y_{bn} & z_{bn} \end{bmatrix} \tag{5} $$

Translation vector ${}^{a}t_{b}$ is described as

$$ {}^{a}t_{b} = \begin{bmatrix} x_{ag} \\ y_{ag} \\ z_{ag} \end{bmatrix} - {}^{a}R_{b} \begin{bmatrix} x_{bg} \\ y_{bg} \\ z_{bg} \end{bmatrix} \tag{6} $$

Taking advantage of the calibrated relationship between the two camera coordinate systems, we can directly transform the point cloud reconstructed by Scanner 2 to the camera coordinate system of Scanner 1.

3.4 Turntable Coordinate System

All point cloud is finally unified into the turntable coordinate system after the transformation of each coordinate system. The calibration of the turntable coordinate system is to obtain the pose of the measurement coordinate system of the Scanner 1 under the turntable coordinate system.

As is shown in Fig. 5, our approach is to make the Scanner 1 construct the criterion sphere placed on the edge of turntable at different angles by rotating turntable. Then fit the spherical centers of point clouds at each pose. Finally all the spherical centers are fitted into a spatial circle and the obtained center coordinate is the origin of the turntable coordinate system [13]. The transformation matrix of Scanner 1 in the measurement coordinate system relative to the turntable coordinate system is

$$ {}^{t}T_{m} = ({}^{m}T_{c}{}^{c}T_{t})^{-1} \tag{7} $$

where c, m and t represent the coordinate system of camera, measurement and turntable.

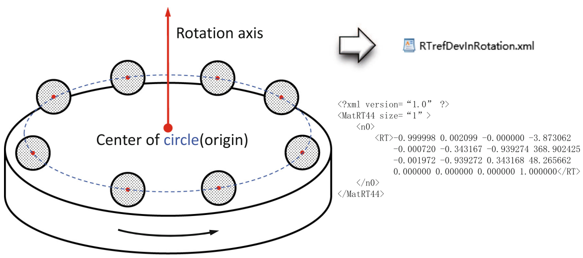

Fig. 5. Rotation axis and transformation matrix

4 Experiments

In this section, we first provide several experiments to show the accuracy of our calibration method and then show the application of blade measurement. The experimental object is a white matte ceramic bat. Sphere 1 is 49.975 mm, sphere 2 is 49.971 mm and distance between centers of sphere is 500.310 mm. And the calibration board is 7 × 7 with ring pattern.

4.1 Results and Analysis

Since the X coordinate of each center of light stripe in the image is fixed, we extract the light stripe 200 times from a single image of criterion sphere at the same position to test the repeatability of laser stripe extraction. As illustrated in Fig. 6, the random error is analyzed by selecting the same X coordinate interval and comparing the corresponding Y coordinate. The maximum of maximum error is 0.452 pixel and the maximum of standard deviation is 0.188 pixel, which indicates that the repeatability error has little influence on the measurement system.

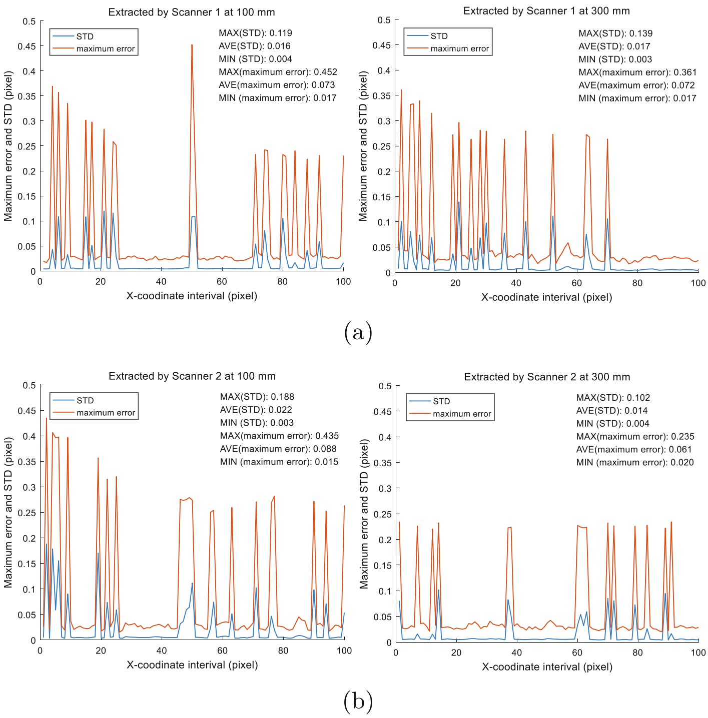

Fig. 6. (a) and (b) are change of Y coordinate corresponding to each X coordinate obtained by extracting the center of laser stripe 200 times from the same position at 100 mm and 300 mm of view field.

As illustrated in Fig. 7, we repeated 50 scans at the same position using a scanner and fitted sphere 1 in order to compare center coordinates and diameters. Table 1 shows the reconstructed repeatability of each scanner. The results indicates the accuracy is within ± 0.02 mm in the view field near the scanner, the maximum standard deviation of center coordinates is 0.011 mm, and that of sphere diameter is 0.005 mm. As shown in Fig. 8, we also tested the accuracy of each registration link. Figure 8(a) analyses the accuracy of motion direction

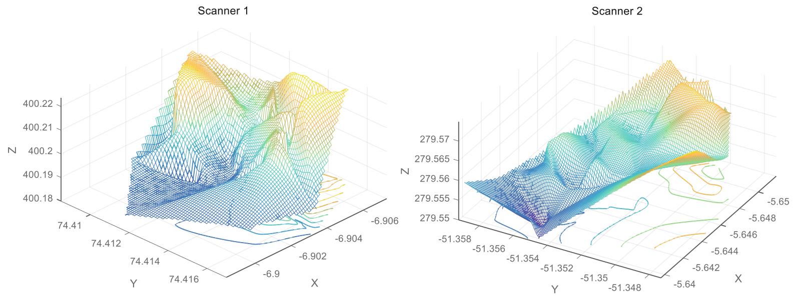

Fig. 7. Spherical center coordinate distribution after 50 times fitting repeatedly

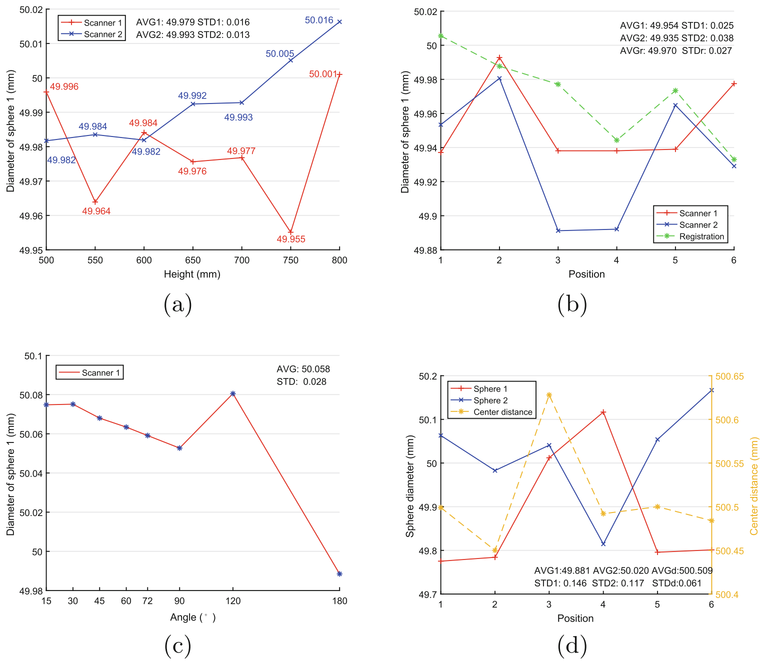

Fig. 8. (*a*) Accuracy of single scanner at different heights (*b*) Registration accuracy between scanners (*c*) Registration accuracy of rotation (*d*) Results of reconstructing bat

calibration. The accuracy decreased with the height increasing, and the maximum deviations of two scanners are 0.026 mm and 0.041 mm. From position 1 to 6 in Fig. 8(*b*), the accuracy of single scanner changes as the sphere is placed from Scanner 1 to Scanner 2. And the maximum error after registration is −0.042 mm. The rotation error analysis of turntable is to rotate sphere 1 around by different angles, fit the point cloud after rotation, and analyze the influence of different angles on the measurement accuracy. The experimental results are shown in

Table 1. Repeatability and accuracy of 50 times scanning by single scanner (*mm*)

Equipment	STD_X	STD_Y	STD_Z	$AVE_{diameter}$	$STD_{diameter}$	MAX_{error}
Scanner 1	0.002	0.002	0.011	49.977	0.005	0.012
Scanner 2	0.004	0.002	0.006	49.973	0.004	0.011

Fig. 8(*c*). Obviously, the smaller the rotation angle, the more rotations, and the lower the accuracy. The maximum error of rotation registration is 0.100 mm. As shown in Fig. 8(*d*), we scanned the bat completely and observed the combined deviation of the sphere diameter and center distance at different positions. All of the rotations in this experiment were performed four times at 90 degrees each time. Due to the error accumulation of mechanical installation, motion mechanism and multi-calibration, the maximum deviation of sphere diameter is −0.200 mm and that of distance between spherical centers is 0.318 mm.

Table 2. Comparison of different methods of blade measurement

Method	Accuracy(*mm*)	Workplace	Time(*min*)	Range(*mm*)
Standard template	0.400	Workshop	10	Customized
CMM	0.002	Lab	25	Max height of 3000
LDS	0.010	Lab	11	$220 \times 180 \times 360$
Our system	0.350	Workshop	3	$400 \times 500 \times 1000$

The comparison among Standard template, CMM, LDS [3] and our system is shown in Table 2. Obviously, our measuring system has high measuring efficiency and large measuring range. And the measurement accuracy also meets the measurement requirements of turbine blade forging.

4.2 Application of Blade Measurement

The specified point & cross section measurement is to measure a number of known coordinate points on the important cross sections of blade. As shown in Fig. 9, we make the template with CAD of blade, point & cross section characteristics and report form. Then the real-time point cloud is automatically imported and registered with CAD. The software calculates the normal deviation of each point and section parameters. For the blade with height of 0.7 m, it takes approximately 3 min from the start of scan to the end of exporting report, which greatly improves the measurement efficiency.

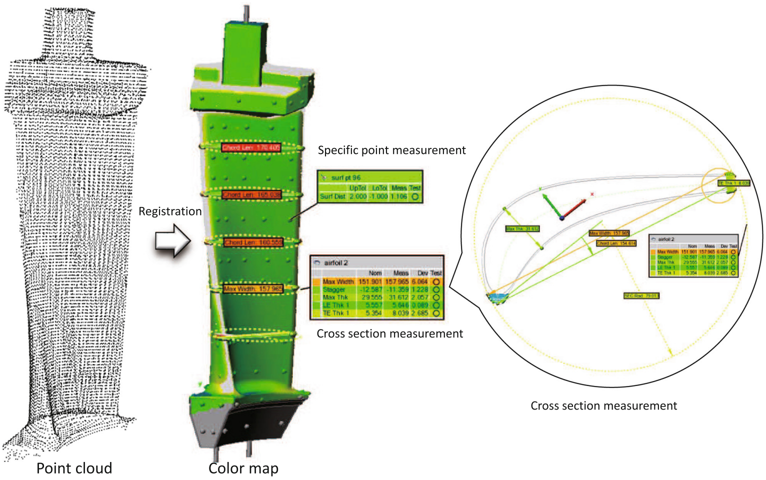

Fig. 9. Measurement process for specified points

5 Conclusion

At present, most of the multi-axis vision measuring devices are designed for small turbine blades. For the profile measurement of large turbine blade forgings, our calibrated system can greatly increase the measurement efficiency and reduce the labor cost. In this paper, we establish the coordinate system model of digital template measurement system, provide the complete calibration process and method, and analyze the error of each calibration link. It is simple and convenient to finish the calibration, and the experimental results show that the accuracy of our calibration method can meet the requirements of turbine blade forging measurement.

Acknowledgments. This research was partially supported by The key research project of Ministry of science and technology (Grant no. 2017YFB1301503) and the National Nature Science Foundation of China (Grant No. 51575332).

References

1. Junhui, H., et al.: Overview on the profile measurement of turbine blade and its development. In: Proceedings of SPIE - The International Society for Optical Engineering, vol. 7656, no. 2 (2010)
2. Fu, Y., et al.: Three-dimensional profile measurement of the blade based on surface structured light. Optik - Int. J. Light Electron Opt. **124**(18), 3225–3229 (2013)
3. Sun, B., Li, B.: A rapid method to achieve aero-engine blade form detection. Sensors **15**(6), 12782–12801 (2015)
4. Sun, B., Li, B.: Laser displacement sensor in the application of aero-engine blade measurement. IEEE Sens. J. **16**(5), 1377–1384 (2016)

5. Zhang, F., et al.: Error modeling and compensation for high-precision non-contact four coordinate measuring system. Key Eng. Mater. **437**, 232–236 (2010)
6. Niola, V., et al.: A method for the calibration of a 3-D laser scanner. Robot. Comput. Integr. Manuf. **27**(2), 479–484 (2011)
7. Vilaca, J.L., Fonseca, J.C., Pinho, A.M.: Calibration procedure for 3D measurement systems using two cameras and a laser line. Opt. Laser Technol. **41**(2), 112–119 (2009)
8. Niu, M., et al.: Research on the method to calibrate structure parameters of line structured light vision sensor. In: International Conference on Mechanics, materials and Structural Engineering 2016 (2016)
9. Dewar, R.: Self-generated targets for spatial calibration of structed-light optical sectioning sensors with respect to an external coordinate system. In: Proceedings of Robots and Vision 1988 Conference, Detroit, pp. 5–13 (1988)
10. Wei, J., Liu, Z., Cheng, F.: Vision sensor calibration method based on flexible 3d target and invariance of cross ratio. In: International Conference on Information Sciences, Machinery, Materials and Energy 2015 (2015)
11. Xu, G., et al.: Global calibration and equation reconstruction methods of a three dimensional curve generated from a laser plane in vision measurement. Opt. Express **22**(18), 22043 (2014)
12. Sun, J., et al.: A vision measurement model of laser displacement sensor and its calibration method. Opt. Lasers Eng. **51**(12), 1344–1352 (2013)
13. Yong-An, X.U., Qin, Y., Jin-Peng, H.: Calibration of the axis of the turntable in 4-axis laser measuring system and registration of multi-view. Chin. J. Lasers **32**(5), 659–662 (2005)
14. Park, S.Y., Subbarao, M.: A multiview 3D modeling system based on stereo vision techniques. Mach. Vis. Appl. **16**(3), 148–156 (2005)
15. Li, J., et al.: Calibration of a multiple axes 3-D laser scanning system consisting of robot, portable laser scanner and turntable. Opt. Int. J. Light Electron Opt. **122**(4), 324–329 (2011)
16. Kurnianggoro, L., Hoang, V.D., Jo, K.H.: Calibration of a 2D laser scanner system and rotating platform using a point-plane constraint. Comput. Sci. Inf. Syst. **12**(1), 307–322 (2015)
17. Pang, X., et al.: A tool-free calibration method for turntable-based 3D scanning systems. IEEE Comput. Graph Appl. **36**(1), 52–61 (2016)
18. Zhang, Z.: A flexible new technique for camera calibration. TPAMI **22**(11), 1330–1334 (2000)
19. Wu, Y., Hu, Z.: PnP problem revisited. J. Math. Imaging Vis. **24**(1), 131–141 (2006)