Solution for vision occlusion based on binocular line-structured light*

WU Zhichao (武志超), **WEI Xiaoxin** (卫晓鑫), **SONG Limei** (宋丽梅)**, and **ZHU Xinjun** (朱新军)
Key Laboratory of Intelligent Control of Electrical Equipment, TianGong University, Tianjin 300387, China

(Received 17 October 2020; Revised 27 November 2020)

Aiming at the problem of the loss of 3D point cloud, due to the occlusion of the field of view in the 3D measurement process, a measurement scheme based on line-structured light with dual-camera is given. In addition, in the line-structured light measurement technology, the traditional light plane calibration is more complicated, and the three-dimensional measurement accuracy is relatively low. For this reason, this paper used the binocular polar line constraint to calibrate the physical parameters of the light plane. Experimental results show that the dual-camera measurement system can obtain high-precision global measurement results. The maximum measurement error is 0.091 51 mm, and the average measurement error is 0.076 05 mm. Compared with the traditional binocular matching method and the traditional laser triangulation method, this method can deal with the problem of field occlusion more effectively, thereby reducing the loss of measurement information in the measurement process.
Document code: A **Article ID:** 1673-1905(2021)07-0432-6
DOI https://doi.org/10.1007/s11801-021-0160-0

Non-contact 3D measurement has a wide range of applications in machine vision, reverse engineering, animation and other fields. Among them, the measurement technology based on line-structured light triangulation has the advantages of simple structure, low cost, non-contact, flexible operation, fast measurement speed, and easy extraction of light strip image information[1,2]. However, there are also some other problems. When the surface of the measurement object is complicated or the surface topography of the object changes drastically, the traditional monocular laser triangulation method and binocular matching method often cause occlusion problems due to the limitation of the field of view, resulting in missing data.

In the study of occlusion problem, Munaro et al used double-line-structured light to scan the object under test at the same time to ensure that multiple structured lights can appear in the system's field of view, thereby reducing the obstruction range of the object under test[3]. Peiravi used two different colored lasers and a color CCD camera. The laser source placed on each side of the camera to minimize occlusion issues[4]. Zhang used two parallel structured light projectors for error compensation in structured light welding seam tracking[5]. However, when calculating the coordinates of the line structured light stripe in the world coordinate system, the accuracy of the single camera measurement is relatively low (compared to the binocular matching), which leads to errors in the calculation of the light-plane equation. Based on the normal vector of the occlusion boundary line, He Bingwei predicted the contour model of the occlusion part, and determines the position of the viewpoint to eliminate the occlusion in combination with the visual space[6]. He Wenjie completed the splicing of point cloud data between frames according to the invariance of the posture of the landmark points, and obtained the complete 3D data of the laser triangulation system[7]. Zhou yuan used the unsupervised characteristics of the density clustering algorithm to solve the problem of disconnection or noise interference during the measurement process, and improves the anti-interference ability of the system[8]. Zhang Bin used two sets of grating-type structured lights, using left and right cross and symmetrical lighting methods to solve the defect measurement of the cylindrical end face of the complex surface[9]. Wang Hao used boundary connectivity analysis and deep learning segmentation algorithms to achieve semantic-level segmentation of projected laser stripes, which solves the noise interference caused by foreign objects on the track during the measurement process[10]. Tang used the "complementary fusion" of the left and right camera light strip images to avoid the problem of missing data caused by sudden changes in surface curvature[11].

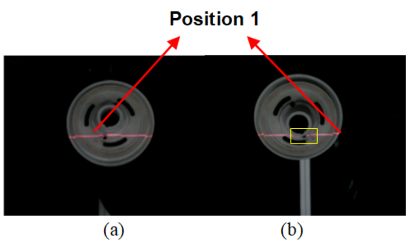
In the line-structured light 3D measurement technology,

* This work has been supported by the National Natural Science Foundation of China (No.61905178), the Natural Science Foundation of Tianjin (No.18JCQNJC71100), and the Program for Innovative Research Team in University of Tianjin (No.TD13-5036).
** E-mail: lilymay1976@126.com

the measurement accuracy of the line-structured light system mainly depends on the structured light plane calibration[12]. The current line-structured light system calibration methods can be divided into two categories. The first category is to perform camera calibration first, and then to perform light knife plane equation calibration. The calibration methods of the light plane mainly include wire drawing calibration method[13], tooth-shaped target calibration method[14] and calibration method based on the invariance of the cross ratio of the three-dimensional target[15] and blanking point method[16], etc. This type of methods usually requires high-precision targets or complex calibration procedures. The second category is to take the line-structured light system parameters as a whole, and to obtain the system parameters by fitting. For example, Zhao HuiJie used BP neural network based on sample training and learning to establish the mapping relationship between two-dimensional image coordinates and three-dimensional space coordinates, and realized the direct calibration of structured light vision system[17]. Sun Yujuan used genetic algorithms to establish the relationship between two-dimensional image coordinates and three-dimensional space coordinates to achieve sensor calibration[18]. However, these methods have some disadvantages such as insufficient accuracy, small number of calibration feature points, and difficulty in processing three-dimensional targets. Zhou Jingbo proposed a line-structured light sensor calibration method based on a reference target. The disadvantage of this method is that it uses one more reference target compared with the classic method, which increases the step of calibration[19]. Peng and Ping et al proposed a line-structured cursor positioning method based on a homography matrix. However, other mechanical aids or a high-precision two-dimensional translation stage are needed, which increases the difficulty and cost of calibration[20,21].

In this paper, the dual-camera solution is adopted to solve the problem of field of view occlusion. By increasing the field of view of the system, the measurement range is enlarged to make the measurement data more complete, and the light plane calibration process is improved. The binocular matching method is used to calibrate the physical parameters of the light plane and to make the system more accurate and more stable.

In a three-dimensional measurement system consisting of a line-structured light source and a camera, when the camera cannot see the structured light beam reflected by the object due to the occlusion of the field of view, the occlusion problem will occur, as shown in Fig.1.



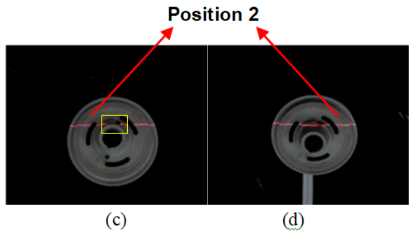


Fig.1 (a) Picture taken by the right camera at position 1; (b) Picture taken by the left camera at position 1; (c) Picture taken by the right camera at position 2; (d) Picture taken by the left camera at position 2

In Fig.1, (a) and (c) indicate that this is a picture with missing light stripe information due to field of view occlusion.

In order to overcome this limitation, this paper proposed to add a camera to expand the field of view of the system, and used an improved light plane calibration method to calibrate the line- structured light measurement system. After calibrating the light plane, by using camera 1 and camera 2 to measure objects simultaneously, the line-structured light binocular three-dimensional measurement system model is shown in Fig.2.

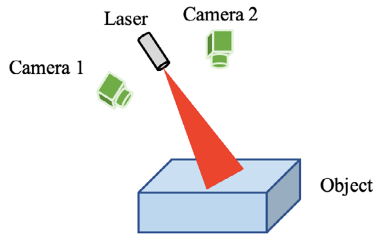


Fig.2 Line-structured light binocular 3D measurement system

The measurement model of the monocular line-structured light sensor is shown in Fig.3, where O_w-$X_wY_wZ_w$ represents the world coordinate system, O_w is the origin of the world coordinate system. O_c-$X_cY_cZ_c$ represents the camera coordinate system. O-xy represents the image coordinate system. O_{uv}-uv represents the pixel coordinate system, and O_{uv} is the pixel origin.

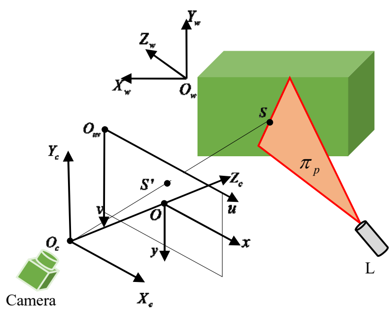


Fig.3 Monocular line-structured light measurement model

It can be supposed that the point S is a point on the curve where the light plane π_p intersects the surface of the measured object, and the point S' is the ideal projection point of the point S on the image plane. Among them, the homogeneous coordinates of the point S in the world coordinate system are $S_w=(X_w, Y_w, Z_w, 1)$. The homogeneous coordinates in the camera coordinate system are $S_c=(X_{ci}, Y_{ci}, Z_{ci}, 1)$. The homogeneous coordinates in the image physical coordinate system are $S_n=(x_n, y_n, 1)$, and the homogeneous coordinates in the pixel coordinate system are $S_{uv}=(u, v, 1)$. According to the camera transmission model:

$$\lambda\begin{bmatrix} u \\ v \\ 1 \end{bmatrix}=\begin{bmatrix} K & \mathbf{0} \end{bmatrix}\begin{bmatrix} R & T \\ \mathbf{0} & \mathbf{1} \end{bmatrix}\begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}. \quad (1)$$

In Eq.(1), λ is a scale factor of any scales. $\boldsymbol{K}$ is the camera's internal parameter matrix. f_x and f_y are the effective focal lengths of the camera in pixels in the directions of x and y. $\boldsymbol{T}$ is a 3×1 translation vector, and $\boldsymbol{R}$ is a 3×3 orthogonal rotation matrix.

In Fig.3, the point S is the intersection of the line O_cS' and the light plane π_p. Therefore, if the equation of the light plane π_p and the equation of the line O_cS' are known, the three-dimensional coordinates of the point S to be measured can be obtained.

In the world coordinate system, the equation of the light plane can be described as:

$$AX+BY+CZ+D=0, \quad (2)$$

where A, B, C, D are the physical parameters of the spatial light plane.

At this point, the simultaneous Eq.(1) and Eq.(2) can realize the calculation of three-dimensional coordinates in space.

The gray barycentric method can be used to extract the sub-pixel coordinates u and v of the point to be measured on the image plane, and to obtain the four physical parameters A, B, C, D of the light plane through binocular line-structured light system calibration. Eq.(4) can be solved by the quaternary linear equation, and can get the coordinates of the point S in the world coordinate system. After the internal and external parameters of the camera are obtained, the binocular polar line matching method is used to calibrate the light plane.

The binocular plane calibration mainly includes four parts: binocular camera parameter calibration, structured light stripe centerline extraction, structured light stripe line three-dimensional reconstruction, and light plane parameter calibration. After calibrating the binocular camera used, the basic matrix $\boldsymbol{F}$ can be obtained. Firstly, the laser stripes are projected onto the surface of plate, then the gray-scale center of gravity method is used to extract the center coordinates of the laser stripes, and by using the outer pole constraints of the binocular camera, the three-dimensional coordinates of the structured light patterns are obtained, as follows: The principle of the outer pole restriction of the binocular camera is shown in Fig.4. *imageL* and *imageR* are the captured images of the left and right cameras respectively, and the straight line OO' is called the baseline. The intersection of the baseline and the two image planes e_l and e_r is called the pole. Line l and line l' are called epipolar line. P is a point on the measured object. P_l and P_r are the projection coordinates of the point P on the left and the right image. The point P_l on the left image corresponds to the matching point P_r on the right image, which must be located on the polar line corresponding to the right image. The corresponding relationship can be expressed as:

$$P_r^{\mathrm{T}}\boldsymbol{F}P_l=0,$$
$$l'=\boldsymbol{F}P_l \ , \quad (3)$$

where $\boldsymbol{F}$ is the basic matrix.

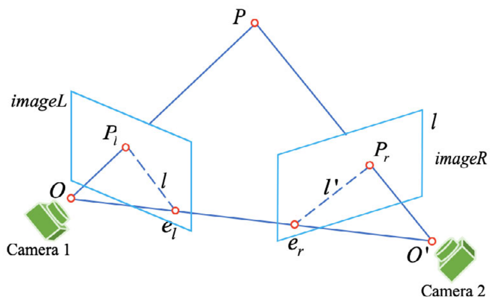


Fig.4 Binocular epipolar line constraint model

According to the principle of epipolar constraint, the left image of each structured light stripe point P_l can match the right image of the corresponding point P_r. By using the least square method of binocular measurement, the three-dimensional coordinates of the point P to be measured in the camera coordinate system can be obtained. By reconstructing the three-dimensional coordinates of multiple structured light stripes, the equation of the structured light plane π_p can be better fitted.

In Eq.(2), X, Y, Z are the three-dimensional coordinates of the light plane π_p point cloud data, and A, B, C, D are the model parameters of the light plane. Supposing the point cloud data to be fitted $S_i(X_i, Y_i, Z_i, 1)$ (i=1,2,3,... n), n points are taken to estimate the plane model parameters, and the estimated plane model parameters can be got as $A_jX+B_jY+C_jZ+D_j=0$. Since there are 4 parameters to be estimated, it needs to be satisfied: $n\geq4$. According to Eq.(4), the deviation e_{rri} can be calculated from the remaining points to the fitted model.

$$e_{rri}=\frac{\left|A_jX_i+B_jY_i+C_jZ_i+D_j\right|}{\sqrt{A_j^2+B_j^2+C_j^2}} \ . \quad (4)$$

If e_{rri} is less than the set threshold, the point is considered to be in the model, and the number of points in the model is counted as J. The eligible points were reselected to estimate the light plane model, the above process several times are repeated, and the corresponding light plane model $A_J X+B_J Y+C_J Z+D_J=0$ are recorded when the number of points in the model reached the maximum value. And it can be used as the best fitting plane. As the number of iterations increases, the plane sought will gradually reach the optimum.

After the light plane π_p calibration is completed, the left and right cameras and the line-structured light emitter each form a monocular line-structured light measurement system. After the measurement is completed, the measurement data of the two cameras are fused together to complete the three-dimensional shape measurement of the object.

As shown in Fig.5, the binocular line-structured light measurement system consists of a precision translation stage, two CCD cameras, two industrial lenses, a line-structured light emitter and a computer. Among them, the repeat positioning accuracy of the precision stage is 0.002 mm. The CCD camera is a black and white industrial camera with a resolution of 1 280 dpi×1 024 dpi, a lens focal length of 8 mm, a line-structured light emitter power of 10 mW, and a wavelength of 650 nm. In the system, the distance between the two cameras is 340 mm, and the angle between the left and right cameras is 36°.

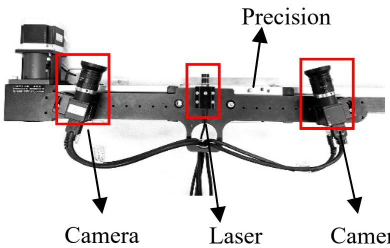


Fig.5 Binocular line-structured light measuring device

In order to obtain the transformation matrix from the world coordinate system to the camera coordinate system, the binocular camera is calibrated stereoscopically using the planar circular calibration target shown in Fig.6, and the calibration result is corrected by using the projection and transformation model. We use the stereo calibration method proposed by Song et al[22] to calibrate the internal and external parameters of the left camera and the right camera. The processing accuracy of the calibration target is 15 μm. The true distance between adjacent centers in the horizontal direction is 10 mm, and the true distance between adjacent centers in the vertical direction is also 10 mm.

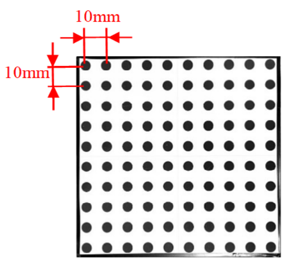


Fig.6 A plane circular calibration target

After the completion of binocular camera calibration, optical plane physical parameters are calibrated. In the experiment, the laser is fixed in the middle of two cameras. The laser stripes are projected onto the surface of target. The target position is changed. The left and right cameras at each position shoot the line structure light stripe image respectively, and the gray gravity center method is used to extract the light stripe central coordinates. Then the outer polar line constraint method of the binocular camera is used to obtain the three-dimensional coordinates of the line-structured light plane in the left camera coordinate system. In theory, only two sets of structured light fringe images can be taken to complete the light plane calibration. In order to reduce the influence of noise factors, the target is placed in multiple different positions in the camera field of view and multiple images are taken. The structured light 3D point cloud reconstruction result is shown in the Fig.7.

Using the method mentioned in the second section to perform plane fitting on all line-structured light point clouds, with the threshold e_{rri} set to 0.1, and the equation for obtaining the optimal light plane is as

$$0.002\,7X-Y-0.009\,3Z+37.102\,5=0. \quad (5)$$

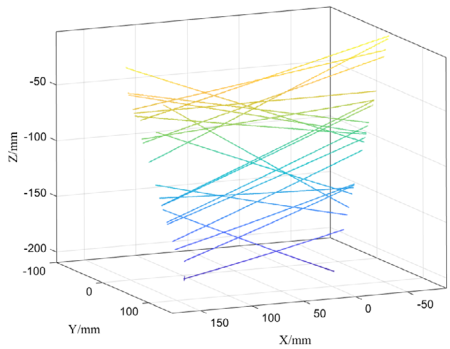
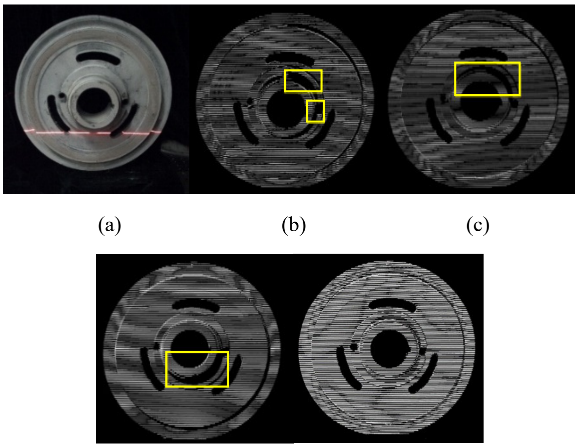


Fig.7 Reconstruction results of multiple laser stripes

By calculating the distance from each point to the fitting plane, the *RMSE* of the system's optical plane calibration is obtained to be 0.019 mm, which meets the precise measurement requirements of complex curved surfaces.

After system calibration, a binocular three-dimensional shape measurement system is formed. In order to verify the feasibility of the method proposed in this paper, the surface of the hub of wheel is measurable by the measurement system after the calibration is completed. For the calibration method proposed in this paper, the accuracy evaluation and uncertainty evaluation are performed by scanning a standard ceramic ball.

The measured object is the automobile hub of wheel, as shown in Fig.8(a), the diameter of the hub of wheel is 20 cm. The distance from the laser to the hub of wheel surface is 600 mm, and the measurement range is 500 mm×400 mm. The calibrated binocular structured light 3D measurement system is used for measurement. The method in this paper generates three-dimensional point cloud, and the data are shown in Fig.8.



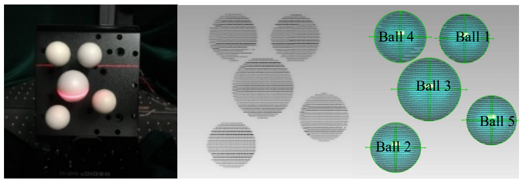
(a) (b) (c)

(d) (e)

Fig.8 (a) The hub of wheel to be tested (photographed by the left camera); (b) Data obtained by the binocular epipolar line constraint method; (c) Point cloud data of left camera; (d) Point cloud data of right camera; (e) Point cloud data of this paper

Fig.8(b) is the three-dimensional point cloud data generated by the binocular epipolar line constraint method. Because binocular epipolar line matching is to reconstruct the data in the common field of view of two cameras, the point cloud data is missing the most; (c) and (d) are the three-dimensional point clouds generated by the left and right cameras respectively. Due to the field of view, the point cloud data is missing; (e) is the point cloud data generated by the method in this paper, and the point cloud data is complete, the recovery effect is best. Compared with the binocular epipolar line constraint method and the single-camera reconstruction result, the dual-camera measurement scheme proposed in this paper can effectively reduce the point cloud data loss caused by the field of view occlusion problem.

After obtaining the light plane equation of the structured light, the left camera and the right camera respectively form a line structured light three-dimensional measurement system with the line-structured light. For the method in this paper, the accuracy of the method is evaluated by scanning the ceramic ball in Fig.9(a). The machining precision of ceramic ball is 1um. In order to increase the effectiveness of the measurement, five standard ceramic balls were scanned 10 times at different positions in the experiment. The measurement distance was 500 mm, and the measurement range was 500 mm×400 mm. The binocular epipolar matching method, the traditional laser triangulation method, and the method in this paper are used to reconstruct the surface of the ceramic ball. Among them, a set of measurement data reconstructed by the method in this paper is shown in Fig.9(b), and the data obtained by fitting is shown in Fig.9(c). The least squares method is used to fit the radius and the center of the standard ceramic ball.



(a) (b) (c)

Fig.9 (a) Standard ball to be tested; (b) Scan data of the method in this paper; (c) Standard ball fitting

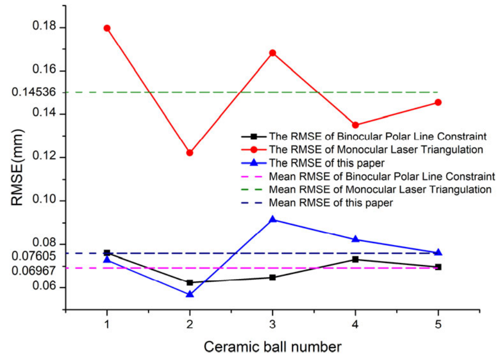


Fig.10 Measuring errors of three methods

In order to test the measurement uncertainty of this method, we calculated the distance from each point of the three-dimensional data of ball 3 to the center of the fitted ball (as shown in Fig.11). According to GB/T 27418-2017, the measurement uncertainty u of this method is obtained by calculating the standard deviation between the measured value and the true value of ball 3 diameter. According to the true value of the standard sphere radius, which is 25.398 5 mm, we get u=0.103.

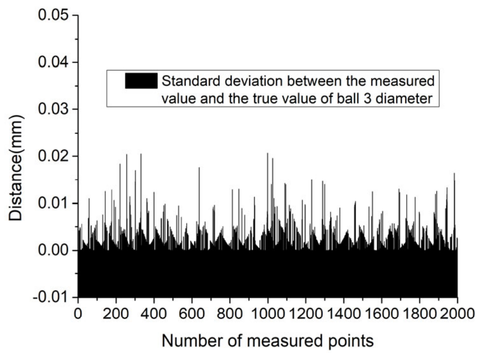
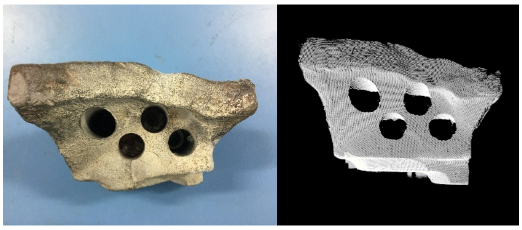


Fig.11 Standard deviation between the measured value and the true value of ball 3 diameter

In addition, this method can be used to reconstruct 3D data on the surface of an irregular workpiece, as shown in Fig.12. It can be seen from Fig.12 that the system in this paper is very effective in restoring the 3D information on the surface of irregular objects and can meet the needs of measurement.

(a) Front of irregular workpiece and scan result



(b) Top of irregular workpiece and scan result

Fig.12 Measurement experiment

In this paper, the disadvantages of 3D restoration of line-structured light are studied, and a measurement scheme to solve the occlusion of light bars is proposed. By using dual cameras to increase the field of view of the system, the complete 3D measurement data of the surface of the object to be measured is obtained. By comparing the measurement effects of monocular measurement, binocular matching method and the method in this paper, this scheme is feasible and can effectively reduce the problem of point cloud missing caused by occlusion of the field of view. For line-structured light plane calibration, in order to improve the calibration precision, the binocular polar line constraint method is used for light plane calibration and simplifing the calibration process. Compared with the traditional monocular line structured light measurement system, it improves the calibration accuracy of the light plane and the stability. Through constructing the system of hardware and software platform to verify the parameters such as accuracy, uncertainty, the method can flexibly be applied to three-dimensional topography measurement of objects, and can be used in the human body scanning, Weld Tracking, mould positioning, etc.

References

[1] Sun Hai-bin, Wang Xing-hai, Chen Jun and Sun Ping, Optoelectronics Letters **12**, 237 (2016).

[2] Thi-Trang Tran and CheolKeun Ha, International Journal of Control Automation and Systems **16**, 2432 (2018).

[3] Matteo Munaro, Stefano Michieletto, Edmond So and Dan iele Alberton, Fast 2.5D Model Reconstruction of Assembled Parts with High Occlusion for CompletenessInspection, International Conference on Machine Vision, 2011.

[4] Ali Peiravi and Behrai Taabbodi, Journal of American Science **6**, 80 (2010).

[5] S. Gao, M. Zhao, L. Zhang and Y. Zou, Dual-Beam Structured Light Vision System for 3D Coordinates Measurement, In Proceedings of the 7th World Congress on Intelligent Control and Automation, 3687 (2008).

[6] He Bingwei, Lin Dongyi, Chen Zhipeng and Ding Hui, Chinese Journal of Lasers **38**, 196 (2011). (in Chinese)

[7] He WenJie and He SaiXian, Laser Journal **41**, 16 (2020).

[8] Zhou Yuan, Meng XiangQun, Jiang DengBiao and Tang HouJun, Chinese Journal of Lasers **47**, 12 (2020). (in Chinese)

[9] Zhang Bin, Yang Tengda, Song Wenhao, Li Fengyu and Liu Mengmeng, Journal of Zhengzhou University **51**, 11 (2019).

[10] Wang Hao, Research and Application of Dynamic Measuring Method of Rail Profile Based on Structured Light Projection, China Academy of Railway Sciences, 2018.

[11] Tang RuiYi, Study on Key Techniques of Vision Measurement for Complex Optical Surface, TianJin University, 2018.

[12] YU Lewen, Zhang Da and Zhang Yuansheng, Journal of Optoelectronics•Laser **27**, 156 (2016). (in Chinese)

[13] Cui Ximin, Li Cong, Yuan Debao, Hong Xueqian and ZHAO Yi, Science & Technology Review **32**, 64 (2014).

[14] Duan F J, Liu F M and Ye S H, Chinese Journal of Scientific Instrument **21**, 108 (2000). (in Chinese)

[15] Jibin Z and Tianfei C, Acta Optica Sinica **35**, 1 (2015). (in Chinese)

[16] Zhenzhong Wei, Mingwei Shao, Guangjun Zhang and Yali Wang, Optical Engineering **53**, 1709 (2014).

[17] Huijie Zhao, Shaoguang Shi, Hongzhi Jiang, Ying Zhang and Zefu Xu, Optics Express **25**, 10413 (2017).

[18] Yujuan Sun, Xiaofeng Zhang, Qingtang Su and Beijing Chen, Soft Computing **22**, 477 (2018).

[19] Zhou Jingbo, Li Yuehua, Qin ZhiYing, Huang FengShan and Wu Zhe, Acta Optica Sinica **39**, 0412005 (2019). (in Chinese)

[20] Peng Qianzhi, Yang Xuerong, Cheng Siyuan and Lu Wenge, Journal of Mechanical & Electrical Engineering **36**, 613 (2019). (in Chinese)

[21] Ping Yishan and Liu Yuankun, Opto-Electronic Engineering **46**, 180677 (2019).

[22] Li Mei Song, Ming Ping Wang, Lu Lu and Huang Jing Huan, Optics & Laser Technology **39**, 1413 (2007).