euspen's 21st International Conference & Exhibition, Copenhagen, DK, June 2021
www.euspen.eu

An iterative calibration method for improving absolute measurement accuracy of stereo deflectometry

Yongjia Xu [1,*], Feng Gao [1], Yuemin Wang[1,2] & Xiangqian Jiang [1]

[1] EPSRC Future Metrology Hub, University of Huddersfield, Huddersfield, HD1 3DH, UK
[2] School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, China

*Correspondence: Y.Xu2@hud.ac.uk; Tel.: +44-7510-953359

Abstract
Stereo deflectometry is a measurement technique for specular surfaces with the advantages of full-field, non-contact and fast measurement. In this paper, a calibration method is investigated to enhance absolute measurement accuracy of stereo deflectometry. Traditional calibration method applies a flat mirror to obtain geometrical parameters of stereo deflectomety by placing the mirror at several space positions. Calibration errors introduced in this process result in inaccurate absolute measurement of stereo deflectometry. In order to improve calibration accuracy, a novel iterative algorithm based on a specular step gauge is explored. Calibration results obtained by traditional calibration method are used as initial input. A step gauge is measured based on the input. Calibration parameters are optimized through an iterative process by obtaining the most accurate measurement data of the step. In order to test the developed method, Two samples including a specular step gauge and a specular circle step are measured with a stereo deflectometry system. Comparison studies are conducted by measuring the samples based on CMM (Coordinate Measuring Machine) and stereo deflectometry with optimized parameters and unoptimized parameters. Experimental results show the developed method can improve the absolute measurement accuracy of stereo deflectometry from millimetre level to tens of micrometers.

Keywords: Absolute measurement, specular surface measurement, structure surface measurement, stereo deflectometry

1. Introduction

Structured specular surfaces are widely applied in various industrial fields such as precision manufacturing, aerospace, intelligent lighting, and automotive manufacturing. Three-dimensional (3D) form accuracy of the structured surfaces directly affects system performance and product quality. However, it is still a challenging assignment for current metrologies to measure structured and discontinued specular surface with good accuracy and speed [1-2]. Stereo deflectometry [3-4] is one of Phase Measuring Deflectometry (PMD) [1-5] technique, which consisting of two imaging sensors and a fringe displaying screen. It is normally applied for specular surfaces without discontinuity because it is sensitive to surface slope variation compares to surface position and slope integrations are used for surface reconstructions [1-5]. High accuracy absolute surface measurement remains a challenge to PMD [6-7]. Form data of measured surface is calculated based on spatial geometric relationship of optical elements in PMD system. Since the geometric relationship is obtained by using calibration, calibration error has serious impact on measurement accuracy of PMD [1-5, 8-10]. Self-calibration methods [9-10] are explored to increase the calibration accuracy of PMD with the advantage of preventing error caused by external calibration tools. By using self-calibration method, stereo deflectometry can achieve good accuracy in the form measurement of continuous specular surface [9-10]. However, our experiments demonstrate that there are errors existing in the absolute measurement of stereo deflectometry when calibrating the system with self-calibration method [9-10].

In order to solve this problem, a calibration method is investigated to enhance absolute measurement accuracy of stereo deflectometry by optimising calibration parameters based on a specular step gauge. Section 2 describes principle of stereo deflectometry and the proposed method. Experiment verifies the method through comparison studies by measuring two specular samples in Section 3. Conclusion is addressed in Section 4.

2. Principle and method

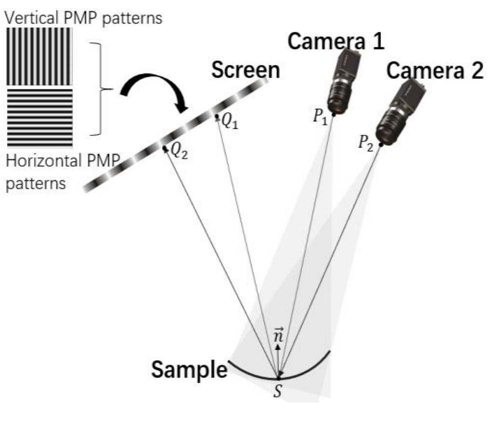

Figure 1. Illustration of measurement principle of stereo deflectometry.

The basic measurement principle of stereo deflectometry is the law of reflection, as illustrated in Figure 1. When regular fringe patterns are reflected by a specular surface, reflection fringes are deformed due to the modulation of the shape of the surface. Surface point S can be measured based on its image points P_1

, P_2 in Camera 1 and Camera 2, and corresponding points Q_1, Q_2 on a displaying screen by matching equivalent normal vectors of S.

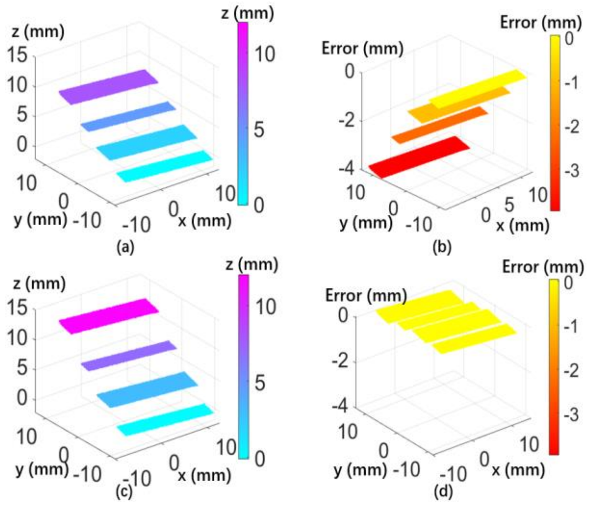

Figure 2. Comparison of measurement data. (a) Original measurement result before compensation; (b) error of original measurement; (c) measurement data after compensation; (d) error of compensated measurement data.

After calibrating a stereo deflectometry system based on self-calibration method [9-10], absolute 3D coordinate of a specular step gauge is obtained, as shown in Figure 2(a). The step gauge is also measured by a Coordinate Measuring Machine (CMM) as a reference. Depth difference between measurement results obtained by stereo deflectometry and CMM is displayed in Figure 2(b). Table 1 compares details of measurement difference between stereo deflectometry and CMM. The distance between the second step and the first step is expressed by $\boldsymbol{h_{21}}$. $\boldsymbol{h_{31}}$ and $\boldsymbol{h_{41}}$ represent the distance between the third step and the first step, and the distance between the fourth step and the first step respectively. Measurement difference of $\boldsymbol{h_{21}}$, $\boldsymbol{h_{31}}$, $\boldsymbol{h_{41}}$ between stereo deflectometry and CMM are denoted with $|\Delta\boldsymbol{h_{21}}|$, $|\Delta\boldsymbol{h_{31}}|$, and $|\Delta\boldsymbol{h_{41}}|$. Figure 2(b) and Talbe 1 clearly demonstrate that there is millimetre-level measurement error existing in oribinal absolute measurement data of stereo deflectometry. Another comparison beween stereo deflectometry and CMM regarding the ratio of step distance is conducted in Table 2. It is noticed that the ratio obtained by the two instruments are similar. Based on this conclusion, a method is developed to compensate absolute measurement error of stereo deflectometry by adjusting the scaling factor of its measuring coordinate system.

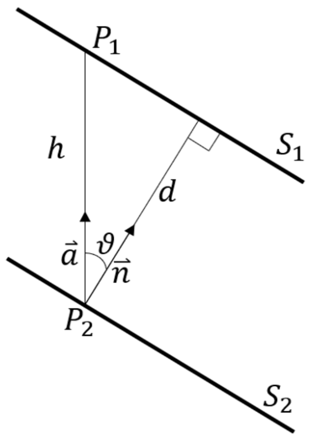

Figure 3. Illustration of the proposed compensation method.

Figure 3 illustrates the method for calculating the scaling factor α, where $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ represent two step planes of the measured step gauge. $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ are two points on $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ with coordinates of $(\alpha x, \alpha y, \alpha z_1)$ and $(\alpha x, \alpha y, \alpha z_2)$ respectively. The distance between $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ is denoted with h. The measured distance between $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ is expressed with d, which can be calculated according to Equation (1).

$$d = \mathrm{h}\cos(\vartheta) \tag{1}$$

where $\cos(\vartheta)$ can be obtained according to Equation (2).

$$\cos(\vartheta) = \frac{\vec{a}\cdot\vec{n}}{|\vec{a}||\vec{n}|} \tag{2}$$

where $\vec{a}$ and $\vec{n}$ are two space unit vectors. $\vec{a}$ equals (0,0,1). $\vec{n}$ is the normal vector of the step surface and can be obtained from the measurement data of stereo deflectometry. α can be calculated by minimizing the following functional:

$$\sum_{i=1}^{m} \left|\bar{d}_i - d_i(\alpha)\right|^2 \tag{3}$$

where $\bar{d}$ is the distance between $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ measured by CMM. m is the number of sampling points on the step surface. Figure 2(c) shows the absolute 3D coordinate compensated by the calculated scaling factor. Depth difference between the compensated data and CMM is shown in Figure 2(d). Talbe 1 lists the obtained $\boldsymbol{h_{21}}$, $\boldsymbol{h_{31}}$, $\boldsymbol{h_{41}}$, $|\Delta\boldsymbol{h_{21}}|$, $|\Delta\boldsymbol{h_{31}}|$, and $|\Delta\boldsymbol{h_{41}}|$ after compensation. It is obvious that $|\Delta\boldsymbol{h_{21}}|$, $|\Delta\boldsymbol{h_{31}}|$, and $|\Delta\boldsymbol{h_{41}}|$ decrease to tens of microns by applying the developed method.

Table 1 Comparison of measurement difference between stereo deflectometry and CMM

	$\boldsymbol{h_{21}}$(mm)/ $\lvert\Delta\boldsymbol{h_{21}}\rvert$(mm)	$\boldsymbol{h_{31}}$(mm)/ $\lvert\Delta\boldsymbol{h_{31}}\rvert$(mm)	$\boldsymbol{h_{41}}$(mm/ $\lvert\Delta\boldsymbol{h_{41}}\rvert$(mm)
Reference (measured by CMM)	2.995 / n/a	6.921 / n/a	11.863 / n/a
Original data (measured by stereo deflectometry)	2.029 / 0.966	4.635 / 2.286	7.905 / 3.958
Data after compensation (measured by stereo deflectometry)	3.041 / 0.046	6.954 / 0.024	11.846 / 0.017

Table 2 Comparison beween stereo deflectometry and CMM in relation to the ratio of step distance

	$\frac{\boldsymbol{h_{31}}}{\boldsymbol{h_{21}}}$	$\frac{\boldsymbol{h_{41}}}{\boldsymbol{h_{21}}}$
Reference (measured by CMM)	2.311	3.961
Original data (measured by stereo deflectometry)	2.284	3.896

3. Experiment

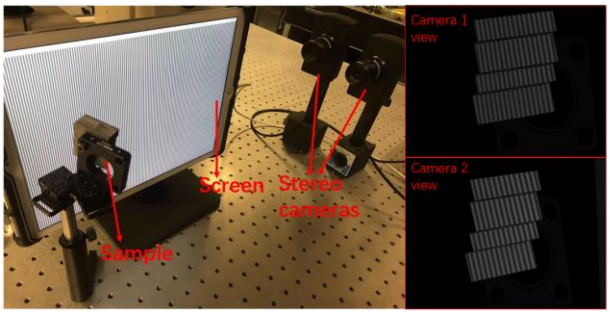

Figure 4. Set up of stereo deflectometry.

In order to verify the developed algorithm, an experiment is conducted with a real stereo deflectometer system, as shown in Figure 4. The system contains two CCD (Charge-coupled Device) cameras (Lumenera Lw235M [11]) and an iPad Pro [12] used as fringe displaying screen. Through the reflection of a specular step gauge, sinusoidal fringe patterns displayed on the screen are captured by the cameras simultaneously, as shown in Figure 4. Initial geometrical parameters of the system can be obtained by placing a flat mirror at several positions [9-10]. Then the obtained geometrical parameters are optimized by using the developed method. A comparison study is conducted by measuring a sepcular step gauge located at an arbitrary position based on optimized parameters and unoptimized parameters. The results is compared in Figure 5 and Table 3. Treating the test result of CMM as the reference value, the absolute measurement error of $\boldsymbol{h_{21}}$, $\boldsymbol{h_{31}}$, $\boldsymbol{h_{41}}$ are dramatically decreased from 0.960 mm, 2.274 mm, 3.950 mm to 0.054 mm, 0.042 mm, 0.006 mm. A specular mirror with three circle steps is also measured with the stere deflectometry system. Measurement results before compensation and after compensation, and measurement difference comparing with CMM are shown in Figure 6. The comparison clearly illustrates the improvement of absolute measurement accuracy of stereo deflectometry by applying the developed method. Using $\boldsymbol{h_{21}}$, $\boldsymbol{h_{31}}$, $\boldsymbol{h_{41}}$ represent the distance from three circle steps to circle base of the mirror. Table 4 shows measurement difference of $\boldsymbol{h_{21}}$, $\boldsymbol{h_{31}}$, $\boldsymbol{h_{41}}$ are dramatically decreased from 1.802 mm, 1.212 mm, 1.562 mm to 0.097 mm, 0.013 mm, 0.014 mm after applying the developed method.

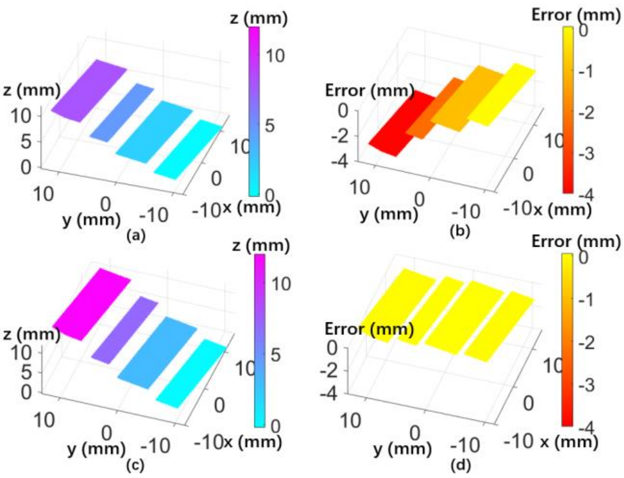

Figure 5. Comparison of measurement data of a specular step gauge. (a) Original measurement result before compensation; (b) error of original measurement; (c) measurement data after compensation; (d) error of compensated measurement data.

Table 3 Comparison of the specular step gauge measured based on optimized parameters and unoptimized parameters

	h_{21}(mm)/ $\|\Delta h_{21}\|$(mm)	h_{31}(mm)/ $\|\Delta h_{31}\|$(mm)	h_{41}(mm)/ $\|\Delta h_{41}\|$(mm)
Reference (measured by CMM)	2.995 / n/a	6.921 / n/a	11.863 / n/a
Original data (measured by stereo deflectometry)	2.035 / 0.960	4.647 / 2.274	7.913 / 3.950
Data after compensation (measured by stereo deflectometry)	3.049 / 0.054	6.963 / 0.042	11.857 / 0.006

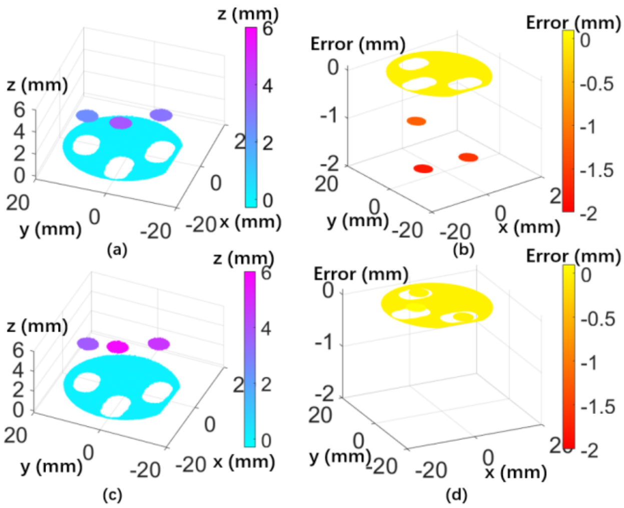

Figure 6. Comparison of measurement data of a specular circle mirror. (a) Original measurement result before compensation; (b) error of original measurement; (c) measurement data after compensation; (d) error of compensated measurement data.

Table 4 Comparison of the specular circle mirror measured based on optimized parameters and unoptimized parameters

	h_{21}(mm)/ $\|\Delta h_{21}\|$(mm)	h_{31}(mm)/ $\|\Delta h_{31}\|$(mm)	h_{41}(mm)/ $\|\Delta h_{41}\|$(mm)
Reference (measured by CMM)	5.617 / n/a	3.676 / n/a	4.672 / n/a
Original data (measured by stereo deflectometry)	3.815 / 1.802	2.463 / 1.212	3.110 / 1.562
Data after compensation (measured by stereo deflectometry)	5.714 / 0.097	3.689 / 0.013	4.658 / 0.014

4. Conclusions

Stereo deflectometry is widely applied in form measurement of continuous specular surface, but seldom tested in the measurement of structure specular surface. This paper discussed error existing in the absolute measurement of stereo deflectometry when using self-calibration methods and method to compensate the measurement error. Based on the fact that the error only relults in the scale change of measurement coordinate system, a method is developed to adjust the scaling factor of the measuring coordinate system of stereo deflectometry by measuring a specular step gauge with known form information. Experimental results verify that the developed method can significantly improve the absolute measurement accuracy of stereo deflectometry.

Acknowledgements

The authors gratefully acknowledge the UK's Engineering and Physical Sciences Research Council (EPSRC) funding of "The EPSRC Future Advanced Metrology Hub" (EP/P006930/1), the funding of "A Multiscale Digital Twin-Driven Smart Manufacturing System for High Value-Added Products" (EP/T024844/1), and the funding of "Next Generation Metrology Driven by Nanophotonics" (EP/T02643X/1).

References

[1] Zhang Z, Wang Y, Huang S, Liu Y, Chang C, Gao F, and Jiang X 2017 *Sensors* **17** 2835

[2] Xu Y, Gao F, and Jiang X 2020 *PhotoniX* **1** 1-10

[3] Knauer M, Kaminski J, and Hausler G 2004 *Proc. SPIE* **5457** 366-376

[4] Xu Y, Gao F, and Jiang X 2018 *Engineering* **4** 806-815

[5] Huang L, Idir M, Zuo C, and Asundi A 2018 *Opt. Lasers Eng.* **107** 247-257

[6] Liu Y, Huang S, Zhang Z, Gao N, Gao F, and Jiang X 2017 *Sci. Rep.* **7** 10293

[7] Zhang Z, Wang Y, Huang S, Liu Y, Chang C, Gao F, and Jiang X 2017 *Sensors* **17** 2835

[8] Li C, Li Y, Xiao Y, Zhang X, and Tu D. 2018 *Opt. Express* **26** 33510-22

[9] Ren H, Gao F, and Jiang X 2015 *Opt. Express* **23** 22060-22068

[10] Xu Y, Gao F, Zhang Z, and Jiang X 2018 *Opt. Lasers Eng.* **106** 111-118

[11] https://www.lumenera.com/

[12] https://www.apple.com/uk/ipad-pro/