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Research Article: Structural parameters analysis of binocular vision measurement system

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Abstract:

This paper proposes a preferred method for the structural parameters of the binocular vision measurement system to improve the accuracy of the system. First, error functions of the structural parameters affecting the measurement accuracy is established on the model of the binocular vision measurement system. Then, the error function is used to theoretically analyze the simple linear structural parameters. For complex nonlinear structural parameters, the preferred range is obtained using MATLAB simulation analysis. when one of the horizontal projection angles of the two cameras is positive and the other one is negative, the system will get better measurement results. At the same time, when the angle between the optical axis and the baseline exceeds 80°, the measurement accuracy of the system is improved. Finally, multiple sets of experimental results indicate the correctness of the preferred range derived from the simulation. Experiments have shown that the preferred range of structural parameters proposed in this paper can improve the accuracy of the binocular vision measurement system.

Index Terms: Binocular vision, Measurement accuracy, Error Analysis, Structural parameters

Introduction:

Binocular vision measurement system (BVMS) are a machine-vision-based measurement method that can directly acquire three-dimensional information of objects. BVMS provide the following advantages: simple structure, wide application range and easy construction. With the continuous maturity and wider application of binocular vision measurement system theory, improving the measurement accuracy of binocular vision measurement system becomes more and more meaningful in practical applications increase. Guo et al. [1] optimized the structural parameters of the optical axis tilt angle α (20°~75°) and focal length f (12mm~15mm) using an enumeration method. They determined that the average integrated measurement error reaches its minimum when the optical axis inclination angle is 45°. In the case of a certain α, increasing the focal length can reduce the average integrated measurement error. However, these observations lack corresponding theoretical analysis. Liu et al. [2] established a measurement model for binocular vision, and determined by means of a simulation analysis that the measurement accuracy improves when the angle between the optical axis and the baseline is between 30° and 60°. When considering the optimal angle between the optical axis and the baseline, it is assumed that the horizontal projection angles of the two cameras are equal. However, this is not the case in the actual measurement situation. Moreover, there is no corresponding experimental verification. Wang et al. [3] have established a system model for spatial specific point measurements from the perspective of image recognition error, and determined the relationship between the measurement error and the angle between the two optical axes. It is verified by experiments that the calibration error increases with an increase of the angle between the two optical axes at a certain baseline. Moreover, it was shown that the calibration error is less within 60°, so it is recommended to choose an angle between 30° and 60°. Although theories and experiments are available here, the researchers do not consider enough from the Angle of 30°. Zhang et al. [4] considered that the structural parameters such as the baseline distance B and the angle between the optical axis and the Z-axis in binocular stereo vision are only theoretical analysis and difficult to measure. Through innovative design and application of 3D technology to print basic parts, a more sophisticated binocular vision system error analysis comprehensive experimental platform was built. An experiment was carried out on apples at an object distance between 50 cm and 100 cm. In this experiment, the measurement accuracy of the test object was up to 0.3 mm when the angle between the optical axis and the Z axis of 3° and the baseline distance of 10.5 cm. Wang et al. [5] simulated the horizontal projection angles of the two cameras from 10° to 170° and measured the four points in space. It is concluded that the closer the spatial three-dimensional coordinate measurement to the target point is to 10°, the smaller the measurement error is. Zhang and Wang et al. obtained similar conclusions through experimental methods, but did not theoretically analyze the influence of structural parameters on the measurement system. Such a verification of individual cases cannot provide theoretical guidance for production practice.

This paper starts with the establishment of a binocular vision measurement model, analyzes the influence of each structural parameter on the measurement system in detail, and verifies the established theory. The conclusion of this paper have certain guiding significance for the practical application of the project.

Binocular Vision Measurement System Model:

We establish a binocular vision measurement system model as shown in Figure 1. C_1 and C_2 indicate the position of the optical centers of the two camera lenses, respectively. C_1O and C_2O are the optical axes of the two cameras respectively. The distance between the two cameras (baseline distance) is denoted by B. The angles between the two optical axes and the baseline are α_1 and α_2, the focal lengths are f_1 and f_2, respectively. We set the origin O_w of the world coordinate system O_w-$X_wY_wZ_w$ to the center C_1 of the left camera. The O_wX_w axis coincides with the baseline, and the O_wY_w axis is pointed in the vertical upwards direction. The image coordinate systems O_1-x_1y_1 and O_2-x_1y_1 of the left and the right camera are on their respective image planes, and the origin is at the midpoint of the image plane. M denotes any measured point in the intersection field of view. The image points on the two camera image planes are denoted by $m_1(x_1, y_1)$ and $m_2(x_1, y_1)$ respectively. The horizontal projection angles of the image points m_1 and m_2 on the optical centers of the two camera lenses are β_1 and β_2, the vertical projection angles are γ_1 and γ_2, respectively. M' is the projection point of the measured point M onto the xoz plane. According to the geometric relationship within the triangle c_1c_2M', the following conclusion can be drawn.

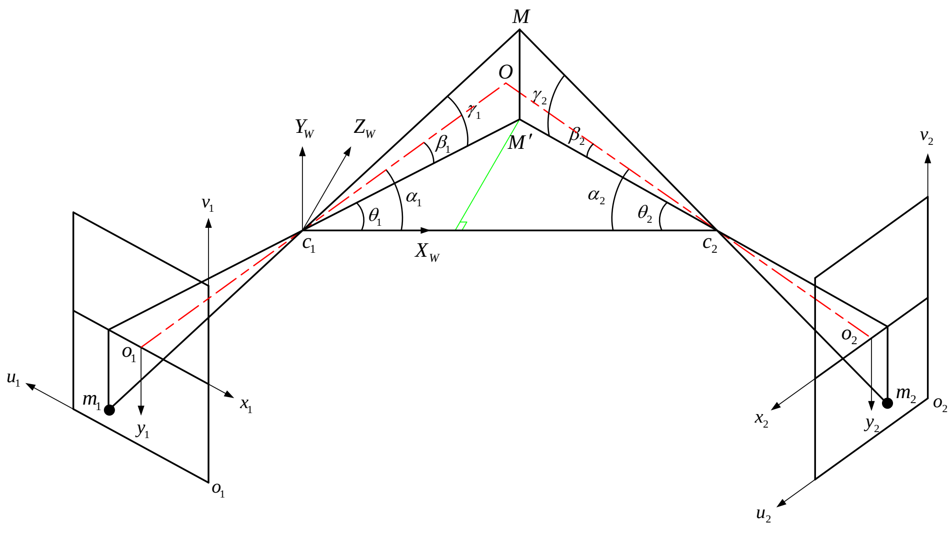

Figure 1: Binocular vision measurement system model

$$X_w = Z_w \times \cot\theta_1 \quad (1)$$

$$B = Z_w \times (\cot\theta_1 + \cot\theta_2) \quad (2)$$

$$\theta_1 = \alpha_1 + \beta_1 \quad (3)$$

$$\theta_2 = \alpha_2 + \beta_2 \quad (4)$$

$$\tan\gamma_1 = \frac{Y_w \sin\theta}{Z_w} \quad (5)$$

According to the above Equations (1)-(5), the three-dimensional coordinates of the point M in the world coordinate system can be obtained.

$$\begin{cases} X_w = \dfrac{B\cot\theta_1}{\cot\theta_1 + \cot\theta_2} \\ Y_w = \dfrac{Z_w \tan\gamma_1}{\sin\theta_1} = \dfrac{Z_w \tan\gamma_2}{\sin\theta_2} \\ Z_w = \dfrac{B}{\cot\theta_1 + \cot\theta_2} \end{cases} \quad (6)$$

where

$$\tan\gamma_1 = \frac{y_1 \times \cos\beta_1}{f_1}$$

$$\tan\gamma_2 = \frac{y_2 \times \cos\beta_2}{f_2}$$

$$\beta_1 = \arctan\frac{x_1}{f}$$

$$\beta_2 = \arctan\frac{x_2}{f}$$

Analysis of Measurement Error:

Error functions of the structural parameters affecting the measurement accuracy is established on the model of the binocular vision measurement system. Due to the many structural parameters affecting the measurement accuracy, some simple linear parameters are analyzed first, and then the complex nonlinear parameters are further analyzed.

A. Error Function of Structural Parameters:

In order to simplify the calculation, we change (6) to:

$$\begin{cases} X_w = F_X(b,\alpha,f,x_1,y_1,x_2,y_2,z) \\ Y_w = F_Y(b,\alpha,f,x_1,y_1,x_2,y_2,z) \\ Z_w = F_Z(b,\alpha,f,x_1,y_1,x_2,y_2,z) \end{cases} \quad (7)$$

Let the acquisition accuracy of the left and the right camera in the *X* direction be δx_1 and δx_2; and the acquisition accuracy in the *Y* direction are δy_1 and δy_2 respectively. Then the measurement accuracy of the point *M* in the *X* direction, the *Y* direction and the *Z* direction can be obtained using Equations 8, 9 and 10.

$$\Delta X = \sqrt{(\frac{\partial X}{\partial x_1}\delta x_1)^2 + (\frac{\partial X}{\partial x_2}\delta x_2)^2} \quad (8)$$

$$\Delta Y = \sqrt{(\frac{\partial Y}{\partial x_1}\delta x_1)^2 + (\frac{\partial Y}{\partial y_1}\delta y_1)^2} \quad (9)$$

$$\Delta Z = \sqrt{(\frac{\partial Z}{\partial x_1}\delta x_1)^2 + (\frac{\partial Z}{\partial x_2}\delta x_2)^2} \quad (10)$$

According to the theory of function error and error synthesis analysis [6], the error in the direction of the three coordinate axes can be expressed as:

$$\begin{cases} \Delta X_w = \sum_i \frac{\partial F_X}{\partial i}\cdot\Delta_i \\ \Delta Y_w = \sum_i \frac{\partial F_Y}{\partial i}\cdot\Delta_i \\ \Delta Z_w = \sum_i \frac{\partial F_Z}{\partial i}\cdot\Delta_i \end{cases} \quad (11)$$

where *i* is b, α, f, x_1, y_1, x_2, y_2 or z. 7 of these 8 parameters are independent of each other so only 7 parameters are used in the calculation. Δ_i is the variable error where $i = b, \alpha, f, x_1, y1, x_2, y_2, z$. $\partial F_K/\partial i$ is defined as transfer coefficient of corresponding coordinate error of variable $K = X, Y, Z$.

We use the error in three directions to represent the integrated measurement error of the coordinates of the measured point:

$$\Delta = \sqrt{\sum_K\sum_i(\frac{\partial F_K}{\partial i}\cdot\Delta_i)^2} = \sqrt{\sum_i(\varphi_i\Delta_i)^2} \quad (12)$$

where φ_i is the integrated error transfer coefficient.

$$\varphi_i = \sqrt{\sum_K(\frac{\partial F_K}{\partial i})^2} \quad (13)$$

The mathematical model of the binocular vision measurement system is a nonlinear model in multiple parameters. The parameters that contribute to the measurement error in the system are numerous and the proportions vary. The transfer function of the structural parameter error of the binocular vision system can be obtained from Equation (6)-(13).

$$\varphi_B = \frac{\sin\theta_2}{\sin(\theta_1+\theta_2)\cos\beta_1} \quad (14)$$

$$\begin{cases} \varphi_{\alpha_1} = \Phi_1\sqrt{1+\frac{\tan^2\gamma_1}{\sin^2\theta_1}\left[\sin\theta_2 - \sin(\theta_1+\theta_2)\cos\theta_1\right]^2} \\ \varphi_{\alpha_2} = \Phi_2\sqrt{1+\frac{\tan^2\gamma_2}{\sin^2\theta_2}\left[\sin\theta_1 - \sin(\theta_1+\theta_2)\cos\theta_2\right]^2} \end{cases} \quad (15)$$

where $\Phi_1 = \frac{B\sin\theta_2}{\sin^2(\theta_1+\theta_2)}$ and $\Phi_2 = \frac{B\sin\theta_1}{\sin^2(\theta_1+\theta_2)}$.

$$\begin{cases} \varphi_{f_1} = \frac{\Phi_1\sin 2\beta_1}{2f_1}\sqrt{1+\frac{\tan^2\gamma_1}{\sin^2\beta_1}\sin^2(\alpha_1+\alpha_2)} \\ \varphi_{f_2} = \frac{\Phi_2\sin 2\beta_2}{2f_2}\sqrt{1+\frac{\tan^2\gamma_2}{\sin^2\beta_2}\sin^2(\alpha_1+\alpha_2)} \end{cases} \quad (16)$$

The following preliminary conclusions can be drawn from Equation (14)-(16).

1) The error in the baseline distance B has no effect on the binocular vision measurement system. Its contribution to the overall system error is derived from the projection angles of the point measured and the angle between the optical axis and the baseline. However, except for the baseline, the error transfer function of other parameters is proportional to the baseline. Therefore, to meet the design requirements of the binocular vision measurement system, reducing the length of the baseline is beneficial to improve the system accuracy.

2) The error transfer function of the focal length is inversely proportional to the focal length. Increasing the focal length is beneficial to the accuracy of the system.

3) The transfer function increases as the vertical projection angle increases. Reducing the vertical projection angle is beneficial to the system accuracy.

The influence of the projection angle and the angle between the optical axis and the baseline have on the measurement system is complicated and still needs further analysis.

B. Error Analysis of Projection Angle:

In the binocular vision measurement system, the focal length of the lens of the camera is generally between 8 mm and 75 mm and the image size of a commonly used industrial CCD camera is generally between 1/4 inch and 1 inch. For a fully installed system, some structural parameters of the binocular vision system are fixed. For the parameters that can be calibrated, the calibration error is generally obtained by the calibration software. As the spatial position of measured points changes, the error due to the extraction of image points is related to the according algorithm used.

The projection angle is an important structural parameter in the measurement system and has a significant influence on the measurement accuracy. In order to simplify the calculation of mathematical models, we may wish to set the pixel error $\delta x_1=\delta x_2=\delta y_1=\delta y_2=\delta$ and the focal length $f_1=f_2=f$.

When a binocular vision measurement system measures a specific object, the error increases with the increase of the vertical projection angle, and reaches the maximum error when the vertical field of view angle is at its maximum. Therefore, in this paper we mainly consider the influence that the horizontal projection angle has on the object measurement error. The error function of the horizontal projection angle can be obtained using Equation (17).

$$\Delta = \frac{B\delta}{f\sin(\theta_1+\theta_2)}\sqrt{\begin{aligned}&\cos^2\beta_2\sin^2\theta_1\left[\cos^2\beta_2+\sin(\theta_1+\theta_2)+\frac{\tan^2\gamma_2}{\sin^2\theta_2}(\cos\beta_2\sin\theta_1+\sin(\theta_1+\theta_2)\cos\alpha_2)^2\right]\\&+\cos^2\beta_1\sin^2\theta_2\left[\cos^2\beta_1+\sin(\theta_1+\theta_2)+\frac{\tan^2\gamma_1}{\sin^2\theta_1}(\cos\beta_1\sin\theta_2+\sin(\theta_1+\theta_2)\cos\alpha_1)^2\right]\end{aligned}} \quad (17)$$

Under normal circumstances, the projection angles obtained by different focal lengths with different CCD cameras are not the same.

Please refer to Table 1 for details.

Table 1. Projection Angles

Focal length	Match 1/3" CCD	Match 1/4" CCD
2.8 mm	89.9°	75.6°
3.6 mm	75.7°	62.2°
4.0 mm	69.9°	57.0°
6.0 mm	50.0°	39.8°
8.0 mm	38.5°	30.4°
12 mm	26.2°	20.5°
16 mm	19.8°	15.4°
25 mm	10.6°	8.3°
60 mm	5.3°	4.1°

Considering the actual application, most vision systems have projection angles of less than 40°. According to the above table, our projection angle is selected as 38°. When considering the influence of the projection angle on the systematic error, it is necessary to consider both the vertical and horizontal directions. However, the vertical projection angle is proportional to the error. In order to reduce the computational complexity, we may wish to set the vertical projection angle to be zero. To simplify Equation 17, we set B, f, and δ to a fixed value. The two-dimensional distribution of the error of the horizontal projection angle is obtained using MATLAB simulation, which is shown in Figure 2.

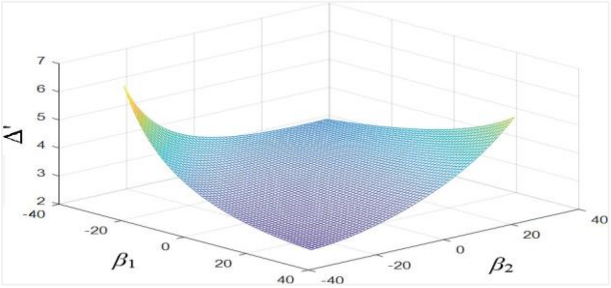

Figure 2. Error distribution of horizontal projection angle $\Delta' = (\Delta \times f) / (B \times \delta)$. β_1 and β_2 represent the horizontal projection angles of the two cameras.

As can be known from Figure 2: 1) The error distribution varies greatly along the same horizontal projection angle of the two cameras. 2) When the horizontal projection angle exceeds 20°, the error changes drastically. 3) The precision increases, when one of the horizontal projection angles of the two cameras is positive and the other one is negative. That is, the measurement accuracy along the border is higher than that for the central part of the object.

C. Error Analysis of The Angle Between the Optical Axis and the Baseline:

Previous research [7] showed that a binocular vision measurement system has the smallest error when the two cameras are symmetrically arranged. That is, the angle between the optical axis and the baseline on two sides are equal. Assuming $\alpha_1=\alpha_2=\alpha$, $\beta_1=\beta_2=\beta$, the error transfer function of the angle between the optical axis and the baseline can be obtained using Equation (18).

$$\varphi_\alpha = \frac{B\sin\theta}{\sin^2(2\theta)}\sqrt{1+\frac{\tan^2\gamma}{\sin^2\theta}\left[\sin\theta-\sin(2\theta)\cos\theta\right]^2} \quad (18)$$

The error distribution of the angle between the optical axis and the baseline can be obtained by simulation, which is shown in Figure 3. The measurement error decreases when the angle between the optical axis and the baseline is smaller or larger. Since the object is too close to the camera when the angle between the optical axis and the baseline is too small. The object may not be completely captured. In order to completely cover the object in the cross-view of the two cameras, the angle between the optical axis and the baseline should be chosen to be larger. When the angle exceeds 80°, the error is lower and the curve is gentler. For this reason the angle between the selected optical axis and the baseline should be larger than 80°.

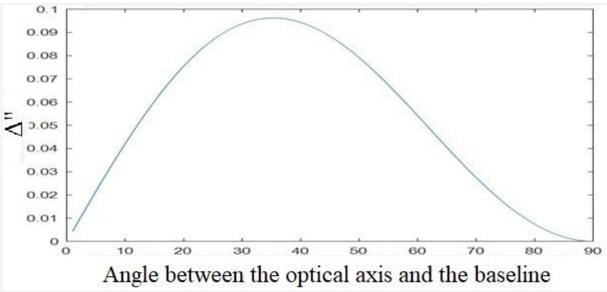

Figure 3. Error distribution of angle between the optical axis and the baseline ($\Delta'' = \varphi\alpha / B$)

Experiment Result:

After the theoretical analysis of the accuracy of binocular vision measurement, a binocular vision measurement platform was built for the experimental analysis. This experimental platform includes the following equipment: two 5-megapixel CCD industrial cameras, quipped with lenses with a focal length of 8mm, a rotating platform and a checkerboard pattern for calibration (with a square size of 6 mm by 6 mm and a manufacturing error of 0.001 mm). The two cameras are symmetrically arranged with a pitch of 200 mm, and the calibration pattern is placed on the platform at a distance of 350 mm to the camera. Therefore, the measurement system has a baseline distance of 200 mm and an object distance of 350mm. The entire measurement system is shown in Figure 4

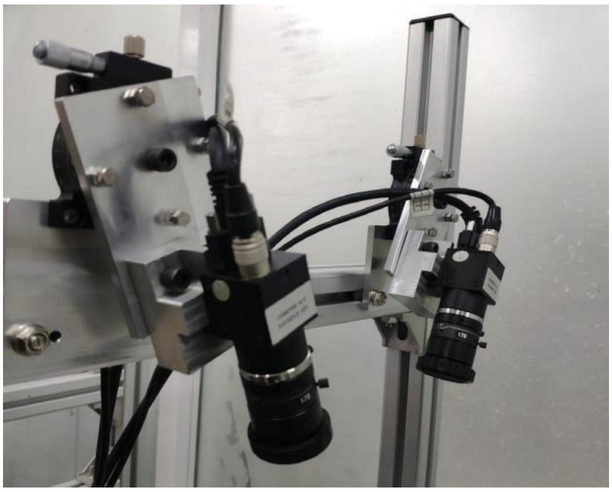

Figure 4. Measurement system

We capture images of the checkerboard by rotating the platform for the following angles between the optical axis and the baseline: 85°, 80°, 75°, and 70°. We collect 12 image pairs in each group and use the acquired images to calibrate the system. For this purpose, we select the photo with the smallest average pixel error out of the collected images to measure the size of the checkerboard.

The grid size of the checkerboard was measured from different angles. Six sets of data were collected in the central part of the checkerboard, and 12 sets are collected along the edges (6 sets on the left and on the right side). The data is shown in Table 2.

Table 2. Measurement result

Angle (°)	Mean of edge measurement (mm)	Average edge relative error	Mean of central measurement (mm)	Average central relative error
85°	5.972	0.46%	5.904	1.6%
80°	5.886	1.9%	5.868	2.2%
75°	5.808	3.2%	5.790	3.5%
70°	5.754	4.1%	5.664	5.6%

Table 2 shows that the measurement error decreases as the angle between the optical axis and the baseline increases. Moreover, the average measurement error of the edge area is smaller than the error of the central part.

In addition to the checkerboard, two iron bars with a width of 10mm and 20mm were manufactured. The length of the two iron bars is 150 mm, and the straightness is less than 0.01. We place each iron bar in the middle of the measurement system and ensure symmetry regarding the two cameras. We measure the width of the iron bar for its middle part and every 15mm to the left and the right. The results of the four angles are shown in Figure 5 and 6.

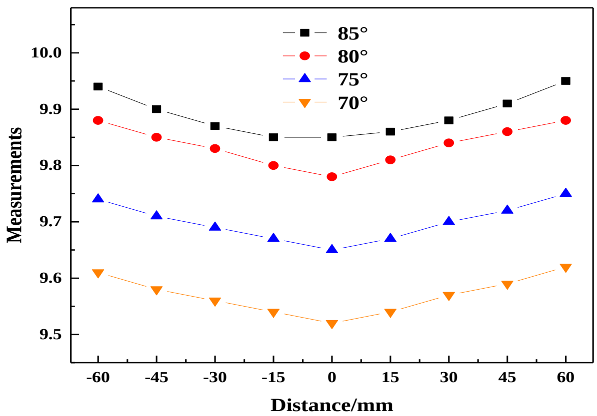

Figure 5. Measurement result of 10mm iron bar

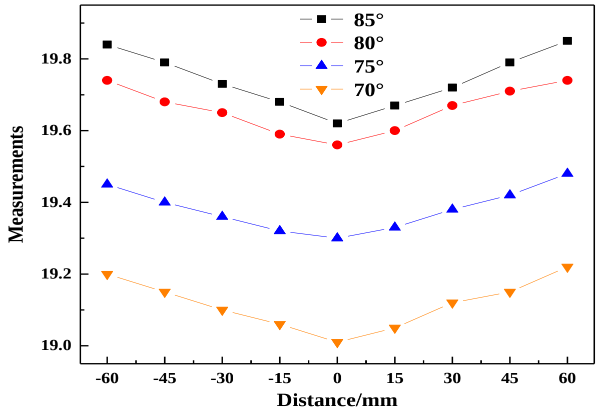

Figure 6. Measurement result of 20 mm iron bar

As shown in Figures 6 and 7, the trends of the curves are consistent with those of the data in Table 2.

Conclusion:

In this paper, we present a mathematical model for a binocular stereo vision measurement system and examine the influence that each structural parameter of the system has on the measurement error. The following conclusions are drawn through a simulation analysis and an experimental verification. First, the baseline has no effect on the entire measurement system. However, the influence of other structural parameters on the measurement system is directly proportional to the baseline. The distance of the baseline should be as small as possible while satisfying the measurement system. Second, the error transfer function of the focal length is inversely proportional to the focal length. Increasing the focal length is beneficial to the accuracy of the system. Third, the measurement error of the entire system is proportional to the vertical projection angle. Regarding the horizontal projection angles, the error varies drastically when the angles exceed 20°. The accuracy is higher when one of the horizontal projection angles of the two cameras is positive and the other one negative. Therefore, when measuring objects, the objects should be placed symmetrically along the center of the baseline. At last, when the angle between the optical axis and the baseline is greater than 80°, the measurement error is low.

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