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Study of zero position's variation for optical sight by using a CCD

© 2019 **Yuanyuan Zhao*, postgraduate student (Physics); Zuojiang Xiao*, PhD (Physics); Xu Liang**, postgraduate student (Physics); Lei Bao***, Ds (Physics)**

**College of Optical and Electrical Engineering, Changchun University of Science and Technology, Changchun, China*
***College of Precision Instruments and Optoelectronic Engineering, Tianjin University, Tianjin, China*
****Jilin Dongguang Precision Machinery Factory, Changchun, China*

E-mail: 1792166418@qq.com

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When measuring the pure zero position′s variation of the high-precision optical sight, it is necessary to eliminate the error caused by repeated installing on the fixture. Traditional measurement methods require two subsystems to obtain pure zero position′s variation. This solution is complex, costly, and has low measurement efficiency. Therefore, this paper proposes a new method based on CCD camera to measure the zero position′s variation of high-precision optical sights. The system uses a collimator, an optical sight, and a CCD camera to build a measurement platform. The coordinate system is established on the CCD imaging surface, and the repeated installation′s error of the sight is obtained by the variation of the image on the CCD image surface by the collimator′s reticle before and after the test. The total zero position′s variation of the sight is measured by the variation of the image on the CCD image surface by the sighting reticle before and after the test. Finally, the pure zero position′s variation is calculated by the difference between the two reticles in the CCD image plane. This paper can measure the pure zero position′s variation of the optical sight with only one CCD camera. The test has verified that the measurement accuracy of the system can reach 2″, which is enough to conform the measurement requirements of high-precision optical sights.

Keywords: *zero position′s variation, CCD, high-precision optical sight, collimator.*

OCIS codes: *260.0260, 120.0120, 080.0080.*

Исследование отклонений нулевого положения марки оптического прицела с использованием ПЗС-матрицы

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При измерении отклонений нулевого положения марки высокоточного оптического прицела необходимо устранить ошибку, возникающую при переустановке прицела. Традиционные методы измерения этих отклонений требуют наличия двух подсистем, что сложно, дорого и не обеспечивает нужной точности. Предложен новый метод, в котором для определения отклонений используется единственная ПЗС-камера, размещённая на измерительной платформе совместно с прицелом и коллиматором. Ошибка переустановки определяется через разницу позиций изображения коллимационной метки на ПЗС-матрице, полученных при последовательных переустановках. Экспериментально подтверждено, что точность системы достигает двух угловых секунд, что удовлетворяет требованиям измерения этой величины для высокоточных оптических прицелов.

Ключевые слова: *ошибка повторных установок, отклонения нулевого положения, ПЗС-камера, коллиматор, оптический прицел.*

INTRODUCTION

The optical sight is mainly used for close combat of armed police and special police, aiming in sea bumpy environment, shooting in the airborne process, etc [1]. The optical sight is an auxiliary device when shooting with firearms. The high-precision sight can maximize the combat effectiveness of the gun [2]. The zero position's variation refers to the deviation of the aiming baseline in the optical sight under the interference of external factors, that is, the deflection angle of the line connecting the center of the reticle to the center of the objective lens, and it is one of the important indicators to measure the accuracy of the optical sight [3, 4]. The traditional method of measuring the zero position's variation is the far point method, the zero position method, and the compensation alignment reading method [5–9]. The methods are not taking into account that when the sight is installed on the fixture for the second time, the space attitude of the sight changes slightly due to the mechanical error of the fixture, as a result, the repeated installation's error is introduced at the measuring [10]. Therefore, the result of the measurement is not a pure zero position's variation, but a zero position's variation including repeated installation's error. For high-precision sights, this error is not negligible.

In this paper, a method for directly measuring the pure zero position's variation of an optical sight with a CCD camera is proposed. A coordinate system is established on the CCD image surface, and a collimator with a reticle is used as a reference target of the sight, calculating the repeated loading error of the sight by the position information of the image formed on the CCD by the reticle of the collimator. Calculate the total zero position's variation by the position information of the image formed on the CCD by the reticle of the sight. The measuring system has a simple composition, which greatly improves the measurement efficiency and measurement accuracy, and reduces the measurement cost. It is of great significance for the production and testing of high-precision optical sights.

MEASURING PRINCIPLE

Fig. 1 is a schematic diagram of the measurement before the optical sight test is performed. To simplify the principle of measurement, it is considered here that the objective lens center and the reticle center line (C_2O_2) are coincided with the axis (C_2C_3) of the lens barrel, the collimator optical axis (O_1C_1) and the optical axis (ab) [11]. R_p, L_p are the reticle and objective lens of the collimator. L_0, R_0 and L_1 are the objective lens reticle and eyepiece of the optical sight. L_c and R_c are the objective lens and reticle of the CCD. O_1' is the image formed that the center point (O_1) of the collimator reticle projects on the optical sight's reticle, and the O_1'' and O_2'' are the images formed that the O_1 and O_2 project on the CCD image surface.

After the test, the zero position of the optical sight is changed, and the measurement principle is shown in Fig. 2. It can be seen from the definition of the zero position's variation that the angle φ between the center of the objective lens and the center of the reticle (C_2O_2)with respect to the optical axis (ab) is the total zero position's variation. It contains errors (α) introduced by repeated installation that is angle of the barrel axis relative to ab. Moreover, the image points of O_1 and O_2 on the CCD image surface were shifted from each other before the test.

According to the geometric relationship in Fig. 2

$$\begin{cases} O_1O_2{}' / l = O_1'''O_2''' / l''' = k \\ \varphi' = k\theta \\ \varphi = \varphi' \end{cases}, \tag{2-1}$$

$$\begin{cases} \alpha' = \arctan O_1'''O_3 / f_c \\ \alpha' = n\alpha \end{cases}, \tag{2-2}$$

where l is the length of collimator's reticle, l''' is the length of the image formed by the collimator on the CCD image, θ is the angle of the theodolite to calibrate the length of the collimator line, n is the magnification of the sight to be tested.

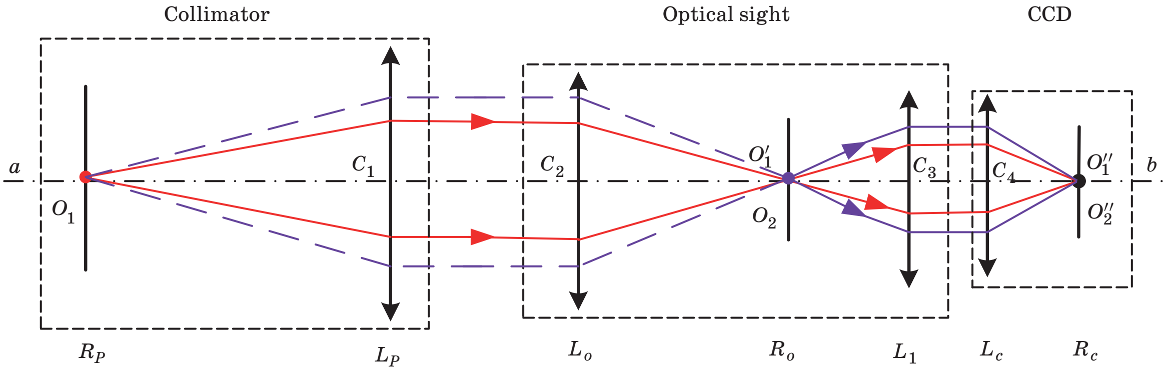

Fig. 1. Schematic diagram of the sight before the test.

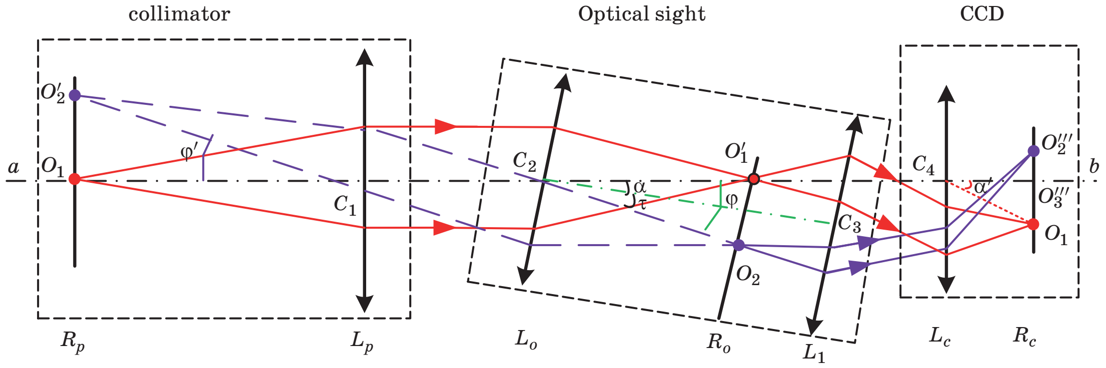

Fig. 2. Schematic diagram of the sight after the test.

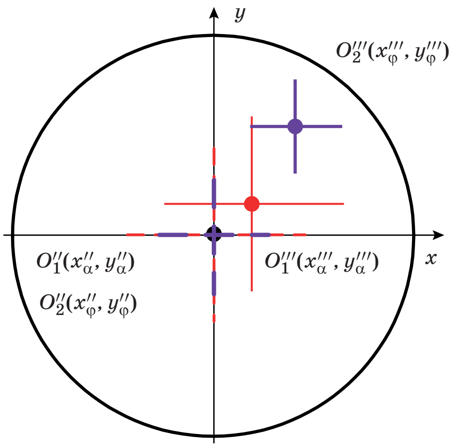

Fig. 3. CCD image surface imaging diagram.

From the formula (2-1), the total zero position's variation (φ) of the optical sight can be obtained. The repeated installation's error (α) can be obtained from the formula (2-2). The difference between the two can be obtained as pure zero position's variation (τ).

Fig. 3 shows the imaging of the CCD imaging surface. First, establish a Cartesian coordinate system in the center of the imaging surface of the CCD camera. $O_1''(x_\alpha, y_\alpha)$ and $O_2''(x\varphi, y\varphi)$ are the coordinates of the image points formed on the CCD by the center of the collimator's reticle and the center of the optical sight's reticle respectively before the test. When the sight was installed on the fixture again after the shootting test, the position of the reticle in the sight and the spatial attitude of the sight changed that compares with before the test, therefore the position of the corresponding image point in the CCD image surface also shifts. As shown in Fig. 3, $O_1'''(x_\alpha, y_\alpha)$ and $O_2'''(x\varphi, y\varphi)$ are the coordinates of the image points formed on the CCD image surface by the center of the collimator's reticle and the center of the reticle of the sight after the test.

In this paper, the angle corresponding to the length of the collimator's reticle is standardized by a Lycra theodolite with an accuracy of 0.5″. And recording the number of pixels occupied by the image of the collimator's reticle on the CCD image surface, thereby calibrating the angle value (δ) corresponding to each pixel.

$$\begin{cases} \varphi_x = \delta\left(x_\varphi''' - x_\varphi''\right)/\Delta \\ \varphi_y = \delta\left(y_\varphi''' - y_\varphi''\right)/\Delta \end{cases}, \qquad (2\text{-}3)$$

$$\begin{cases} \alpha_x = \delta\left(x_\alpha''' - x_\alpha''\right)/\Delta \\ \alpha_y = \delta\left(y_\alpha''' - y_\alpha''\right)/\Delta \end{cases}, \qquad (2\text{-}4)$$

$$\begin{cases} \tau_x = \left|\varphi_x\right| - \left|\alpha_x\right| \\ \tau_y = \left|\varphi_y\right| - \left|\alpha_y\right| \end{cases}, \qquad (2\text{-}5)$$

where Δ is the size of pixel and δ is the angle value represented by each pixel. φ is the total zero position's variation, α is the repeated installation's error, and τ is the pure zero position's variation.

From Equation (2-3), (2-4), the total zero position's variation and the repeated installation's error in the two directions of x, y can be obtained. Then, by formula (2-5), the pure zero position's variation in both directions of x, y can be obtained.

MEASUREMENT SYSTEM DESIGN

When measuring with a CCD, the minimum resolution (accuracy of the measurement system) of the measured angle is determined by the pixel size of the camera [12, 13], that is, the minimum resolution is the angle value represented by one pixel (δ). In order to reduce the error and improve the calibration accuracy, we control the error within 2″ (ie $\delta = 2''$) so as to calculate and select the length of collimator's reticle (l) and CCD focal length (f_c).

In this paper, the effective pixel number of the CCD image plane is 4032×3024, the pixel size is $\Delta = 1.88$ μm, and the focal length of the collimator is 550 mm. The magnification of the optical sight is 3 times. According to the geometric relationship, the mathematical formula of the field of view of the CCD camera is

$$\begin{cases} \gamma = 2\arctan\left(\Delta\ m / 2f_c\right) \\ \gamma = m\delta_{\min} \end{cases}, \qquad (3\text{-}1)$$

where CCD pixel size $\Delta = 1.88$ μm, CCD pixel number $m = 3024$. The focal length of the CCD objective lens ($f_c \approx 193.87$) can be obtained by the formula (3-1). In order to control the measurement accuracy within 2″, a CCD with a focal length of 200 mm was selected.

In order to reduce the error, try to make the image of the collimator's reticle occupy 1/2 of the CCD image surface. The number of pixels occupied by the image formed by the collimator's reticle on the CCD can be obtained

$$S = m / 2, \qquad (3\text{-}2)$$

The angle represented by the collimator's reticle is

$$\theta = S\delta / n, \qquad (3\text{-}3)$$

In the formula, n is the optical sight's magnification.

According to the definition of the angle of field of view, the field of view of the collimator is θ.

$$\theta = 2\arctan\left(1 / 2f_p\right). \qquad (3\text{-}4)$$

In the formula, l is the length of the collimator's reticle, f_p is the focal length of the collimator's lens. From the formula (3-2), (3-3), (3-4), the length of the collimator line can be obtained (l = 2.64 mm). In order to minimize the calibration error, this system selects a collimator with a 3 mm of reticle's length.

EXPERIMENT AND DATA ANALYSIS

Based on the above theoretical analysis of the zero position's variation measurement system, we built a test platform, as shown in Fig. 4. The system mainly includes the light source, the collimator, the optical sight to be tested, the adjustment frame, the CCD camera and the microcomputer processing unit.

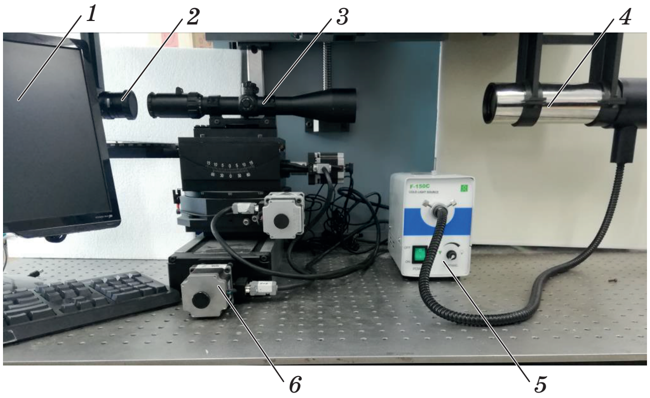

Fig. 4. Measuring the physical map. *1* — computer, *2* — CCD, *3* — optical sight, *4* — collimator, *5* — light source, *6* — adjustment frame.

First, we install the sight on the six-dimensional mount (or fixture), then adjusts the position of the collimator, optical sight and CCD camera to the same height. Turn on the light source and ensure that the image of the collimator's reticle and optical sight's reticle appear together in the center of the CCD image surface. Fixe the position of light pipe and CCD camera. Finally, the measurement accuracy of the zero position's variation and the measurement accuracy of the repeated installation's error are respectively tested. The test results are shown in Fig. 5.

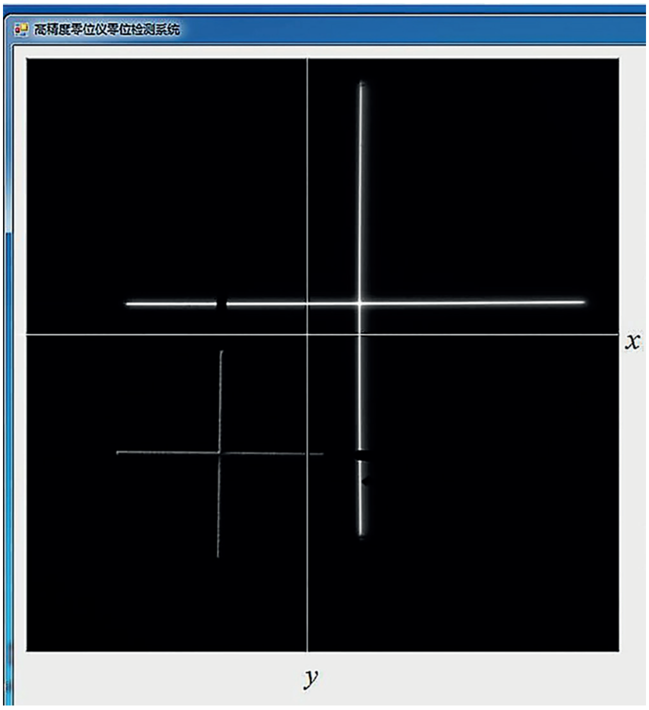

Fig. 5. Test experiment interface/Zero position's variation measurement.

EXPERIMENT AND ANALYSIS

In order to ensure that the measurement results do not include repeated loading errors, we will fix this system on the optical platform and adjust the sight reticle knob while keeping the space attitude of the tested sight unchanged. In order to the reticle is adjusted in steps of 1' each time in the horizontal and vertical directions. The step size is taken as the theoretical value of pure zero position's variation, and the measured value of the CCD camera is compared with the theoretical value in order to evaluate the accuracy of system. The test data is shown in Tab. 1.

It can be seen from the measurement data in the table that the difference between the measured

Table 1. Test data of zero position′s variation in the *x*, *y* direction.

Number	Angle adjustment value of the reticle on *x* axis direction, (degree, minute, second)	Angle adjustment value of the reticle on *y* axis direction, (degree, minute, second)	*X* axis CCD reading, (degree, minute, second)	*Y* axis CCD reading, (degree, minute, second)	The difference between the *x* axis CCD reading and the theoretical true value, (second)	The difference between the *y* axis CCD reading and the theoretical true value, (second)
0	–0°06′00″	–0°06′00″	–0°06′1.3″	–0°06′1.2″	–1.3″	–1.2″
1	–0°05′00″	–0°05′00″	–0°05′2″	–0°05′2.1″	–2.0″	–2.1″
2	–0°04′00″	–0°04′00″	–0°03′58.8″	–0°03′58.2″	1.2″	1.8″
3	–0°03′00″	–0°03′00″	–0°03′1.3″	–0°03′1.3″	–1.3″	–1.3″
4	–0°02′00″	–0°02′00″	–0°01′58.5″	–0°01′58.6″	1.5″	1.4″
5	–0°01′00″	–0°01′00″	–0°00′58.3″	–0°00′59.3″	1.7″	0.7″
6	0°00′00″	0°00′00″	0°00′1.8″	0°00′0.6″	1.8″	0.6″
7	0°01′00″	0°01′00″	0°01′1.8″	0°01′1.3″	1.8″	1.3″
8	0°02′00″	0°02′00″	0°01′58.7″	0°02′1.9″	–1.3″	1.9″
9	0°03′00″	0°03′00″	0°02′59.5″	0°02′59.7″	–0.5″	-0.3″
10	0°04′00″	0°04′00″	0°04′1.6″	0°04′1.5″	1.6″	1.5″
11	0°05′00″	0°05′00″	0°05′1.4″	0°05′2.1″	1.4″	2.1″
12	0°06′00″	0°06′00″	0°06′1.3″	0°05′58.6″	1.3″	-1.4″
AVERAGE					0.42″	0.40″
STDEVP					1.41″	1.40″
					1.98″	

Table 2. Test data for rotation along the *x*, *y* axis

Number	Adjustment amount of the adjustment frame in the *x*-axis direction (degree, minute, second)	Adjustment amount of the adjustment frame in the *y*-axis direction (degree, minute, second)	CCD reading in *x*-axis direction (degree, minute, second)	CCD reading in *y*-axis direction (degree, minute, second)	The difference between the CCD reading and the theoretical true value in the *x*-axis direction (second)	The difference between the CCD reading and the theoretical true value in the *y*-axis direction (second)
0	-0°30′00″	-0°30′00″	-0°29′55″	-0°30′03″	-1.2″	-1.7″
1	-0°25′00″	-0°25′00″	-0°25′05″	-0°25′04″	-1.4″	2.2″
2	-0°20′00″	-0°20′00″	-0°20′04″	-0°20′01″	1.3″	1.5″
3	-0°15′00″	-0°15′00″	-0°14′56″	-0°15′06″	-1.3″	-0.8″
4	-0°10′00″	-0°10′00″	-0°10′05″	-0°10′02″	1.2″	1.2″
5	-0°05′00″	-0°05′00″	-0°05′03″	-0°05′02″	0.9″	1.3″
6	0°00′00″	0°00′00″	0°00′02″	0°00′03″	0.7″	0.8″
7	0°05′00″	0°05′00″	0°04′56″	0°04′57″	1.5″	0.7″
8	0°10′00″	0°10′00″	0°10′06″	0°9′56″	1.4″	1.5″
9	0°15′00″	0°15′00″	0°15′03″	0°15′02″	-0.9″	-1.6″
10	0°20′00″	0°20′00″	0°20′01″	0°20′01″	1.6″	1.3″
11	0°25′00″	0°25′00″	0°25′06″	0°25′03″	2.4″	-1.6″
12	0°30′00″	0°30′00″	0°30′02″	0°29′58″	-1.6″	-1.7″
AVERAGE					0.35″	0.24″
STDEVP					1.35″	1.42″
					1.96″	

value of the CCD and the theoretical value is about 2″ in both directions of x and y axes. The average standard deviation in both directions x and y is 1.98″. It shows that the measurement system has a measurement accuracy of 1.98″ for the pure zero position's variation, which fully conforms the design error of this paper.

MEASUREMENT AND ANALYSIS OF REPEATED INSTALLATION'S ERROR

The repeated installation's error is caused by a change in the spatial attitude of the sight during measurement. In this experiment, the reticle of the sight is fixed, and the space posture of the sight is changed by adjusting the six-dimensional adjustment frame so that the sight is adjusted in the horizontal and vertical directions by 5′ each time. Using this angle value (5′) as the theoretical value of the repeated installation's error, the measured value of the CCD camera is compared with the theoretical value to evaluate the measurement accuracy of the system for repeated installation's error. The test data is shown in Tab. 2:

It can be seen from the measurement data in the table that the difference between the measured value of the CCD and the theoretical value is about 2″ in both directions of x and y axes. The average standard deviation in both directions x and y is 1.96″. It shows that the measurement system has a measurement accuracy of 1.96″ for the repeated installation's error, which fully conforms the design error of this paper.

The experimental results show that the actual measurement results of the system are consistent with the theoretical design results, which proves that the system designed in this paper is feasible. It conforms the measurement requirements for the zero position's variation of high-precision sights.

CONCLUSION

This paper proposes a measurement system based on CCD camera to measure pure zero position's variation. This system can measure the pure zero position's variation of high-precision sights with only one CCD camera. The system abandons the shortcomings of traditional measurement methods such as low measurement accuracy, high cost, and complicated process. Through the theoretical analysis, the experimental system was built and verified. The total zero position's variation was simulated by adjusting the angle of the sight's reticle, and the repeated installation's error was simulated by adjusting the space attitude of the optical sight. Experiments show that the measurement accuracy of the system can reach 2″, which is enough to conform the measurement requirements of high-precision sights.

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