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Error Analysis of Shadow Camera for Measuring Motion Attitude of Large Caliber Projectile

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Abstract. The measurement principle and working process are studied. The motion fuzzy value of measurement system, synchronization error of flash system, Camera distortion error and image feature point extraction error are analyzed. The coordinate measurement error of the measurement system characteristic point is synthesized. On this basis, the attitude measurement error of the measurement system is calculated according to the definition of attitude angle and the error transfer mechanism, and the calculation results show that the error of attitude measurement of projectile is less than 0.8'. The process of error analysis shows that the camera distortion error and feature extraction error are the main errors among many error factors affecting the measurement accuracy.

1. Introduction

With the development of new large caliber artillery, it is urgent to measure the motion attitude of projectile in the field test and appraisal of new type artillery. It is used to identify the aerodynamic coefficients of projectiles, and analyze the firing stability of artillery. And it provides data basis for optimizing the structure of projectiles, studying the coupling mechanism of projectiles and artillery and improving the structure of artillery^[1-4]. Each measurement method has its own characteristics, and is suitable for different measurement environments to achieve different measurement accuracy and measurement range of projectile motion attitude measurement tasks. Because of the particularity of measurement object and measurement environment, the imaging system has some problems, such as small measurement area, low spatial resolution and serious motion blurring, which increase the difficulty of extracting projectile features from measurement images, and restrict the application of high-speed imaging technology in the field of large-caliber projectile motion attitude parameter measurement^{[5][6]}. Based on the existing high-speed imaging technology, this subject intends to study a method for measuring the motion attitude parameters of large caliber projectiles suitable for the outfield environment. The key technologies of this method are deeply studied. On the premise of realizing non-contact measurement, high-resolution and high-definition projectile images are obtained, and the high-precision measurement of projectile motion attitude is realized, which can optimize the design of large caliber artillery and target range. Identification provides reliable experimental data. The technology can also be applied to aerospace, traffic safety, military reconnaissance, target interception, industrial pipeline, biomechanics and other fields where there are a large number of high-speed moving targets. It is of great significance to improve the technical level of transient physical measurement of high-speed moving targets in complex environments.



Different from the previous shadow camera station, the measurement of large caliber projectile motion attitude by shadow camera method should be carried out in the field. Besides the conventional error factors, the calibration measurement errors may also be affected by natural wind, stray light, etc. The calibration principle and working process of shadow camera station for large caliber projectile attitude measurement are studied. The main error factors affecting the calibration accuracy of the system are analyzed, and the errors in the calibration process are analyzed. Calculations show that the measurement error of projectile attitude is less than $0.8'$, and the main source of the error is clarified, which points out the direction for the improvement of the measurement accuracy and the control of the error.

2. Composition and Working Principle of Shadow Camera System

The exterior trajectory section of the existing indoor target trajectory is equipped with several shadow camera stations along the shooting direction, which are used to measure the azimuth of projectile axis at the photographic station. As shown in figure 1, a single shadow camera station is mainly composed of a shadow camera, a pulse laser, a trigger device, an optical system and a reflecting screen. Two shadow cameras are distributed on both sides of the target, with the optical axis obliquely set at 45 degrees, and the reflecting screen is opposite to the shadow camera, which is perpendicular to the optical axis of the camera. Use muzzle signal to start the first timing circuit in the camera controller and open the shutter of the shadow camera. When the projectile flies to the trigger and passes through the detection area, the trigger device outputs a square wave signal to the camera controller, which delays the control of pulsed laser flash to shoot the projectile. Shadows of projectiles are formed on the reflective screen. Shadowgraph of projectile flight can be obtained by shadow camera after being sensitized.

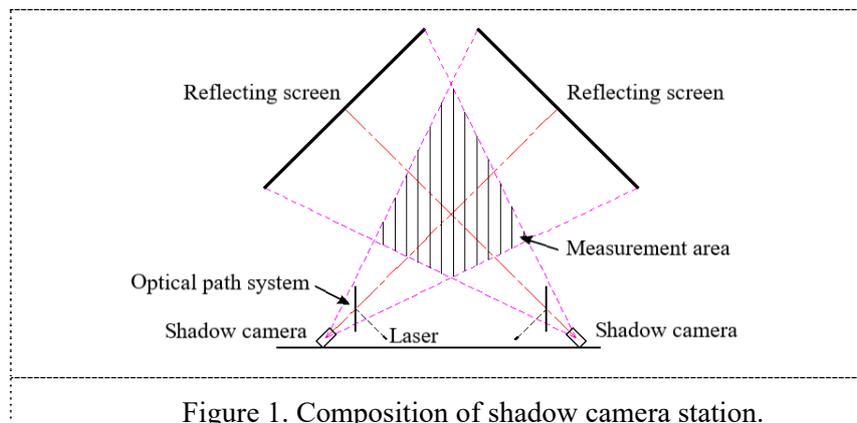


Figure 1. Composition of shadow camera station.

Calibrating the current shadow camera station with the double square nets as the reference material. The calibration of shadow camera station mainly helps to establish the transformation relationship between shadowgraph coordinate system and target space coordinate system, and unifies the used shadow image into the same space coordinate system, so as to calculate the projectile attitude angle.

3. Analysis of error factors affecting measurement

Shadowgraph of projectile is obtained directly from attitude measurement of projectile motion. In the process of processing, the shadowgraph of the reference carrier obtained by calibration is taken as the spatial datum. The projectile feature points are extracted from the image, and the corresponding spatial coordinates are obtained, then the projectile motion attitude angle is obtained. The error sources of attitude measurement are analyzed according to the measurement and data processing process. As shown in figure 2, the measurement error of projectile motion attitude is directly determined by the measurement error of characteristic points. Calibration error, motion fuzzy value, synchronization error of flash system, camera distortion error and image feature point extraction error affect the measurement error of feature point together. Because the calibration system as the spatial datum of system data processing is very complex, this chapter will analyze the calibration error in detail first,

and then calculate the attitude measurement accuracy of the system according to the error transfer mechanism.

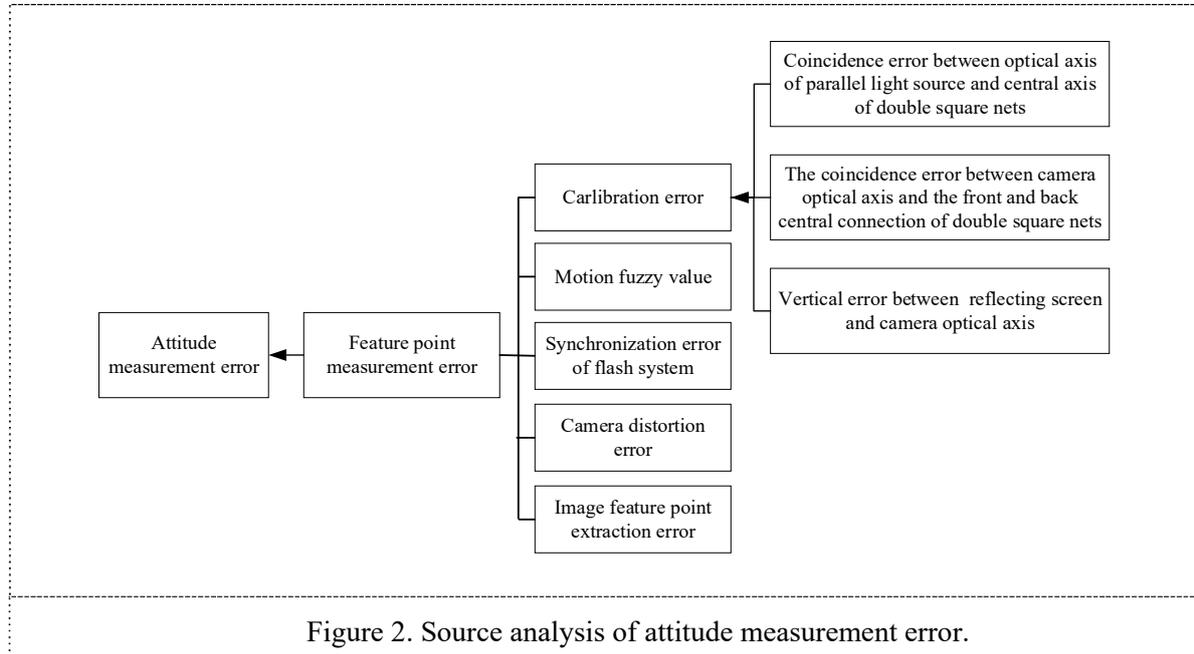


Figure 2. Source analysis of attitude measurement error.

3.1. Measurement error of characteristic points

The coordinate of projectile imaging point on shadow camera is the key of projectile pose calculation. Shadowgraph is the direct mapping of projectile's spatial position. In the imaging process, the projectile feature point mapping position will deviate from the ideal position due to the characteristics of target and imaging devices.

3.1.1. Calibration error. In the process of calibration, the three directions of x, y and z have the same conditions, so it can be considered that the errors of x, y and z are the same, that is $\delta_{x_0} = \delta_{y_0} = \delta_{z_0} = 0.062mm$.

3.1.2. Motion fuzzy value. According to the motion characteristics of projectiles, the motion of projectiles can be simplified to translation along the direction of x and rotation around the projectile axis. The attitude measurement of projectile belongs to dynamic measurement. The image motion blurred due to translational motion along the shooting direction and rotation around the projectile axis. When the rotation speed of 155 mm projectile is generally less than 2000 r/min, the linear velocity of the projectile's edge around the projectile axis is $V_r = \omega_r \cdot r = 20000 / 60 \times 155 / 2 / 1000 = 25.8m / s$.

When the flash time of the pulsed laser is $T = 20ns$, the motion fuzzy value δ_r caused by the high-speed rotation of the projectile is $\delta_r = V_r \cdot T = 25.8 \times 20 \times 10^{-9} = 0.5\mu m$.

Therefore, the motion fuzzy value δ_r caused by high-speed rotation of projectiles can be neglected.

If the translational velocity of the projectile is $V_x = 1000m / s$ along the shooting direction, the motion fuzzy value δ_e caused by the translational motion of the projectile along the firing direction is $\delta_e = V_x T = 1000m \cdot s^{-1} \times 20ns = 0.02mm$.

3.1.3. Synchronization error of flash system. In the real projectile experiment, after the projectile passes through the trigger target, it passes through a certain delay laser flash, and the laser is split by

using the beam-splitting fiber. Because of the fast propagation speed of light, the asynchronization error δ_{Δ} caused by the beam-splitting fiber's length can be neglected.

3.1.4. *Camera distortion error.* Due to the limitation of the manufacturing technology of imaging devices, the camera itself will be distorted. The distortion error of the camera is 0.5 pixel, then $\delta_4 = 0.0935mm$.

3.1.5. *Feature point extraction error.*

- Error of image plane coordinate extraction.
In this paper, the center point of the projectile tail is determined by fitting ellipse based on least square method, and the accuracy is 0.44 pixel. The intersection point of the axis and contour in the image is taken as the feature point of the projectile tip, and its extraction accuracy is estimated to be 0.5 pixel. According to the range method, then $\delta_5 = 0.0935mm$.

- Vertical axis coordinate error of mesh surface.

As shown in figure 3, the vertical axis coordinates of the grid surface in the spatial datum are determined according to the relative distance of the grid surface. Because of the machining error, the distance between the front and back grids will deviate from the theoretical value, resulting in the errors of extracting the vertical axis coordinates of points A and B. The geometric tolerance of grid is 0.05 mm, Therefore, the vertical axis coordinate error of the mesh surface is $\delta_6 = 0.05mm$.

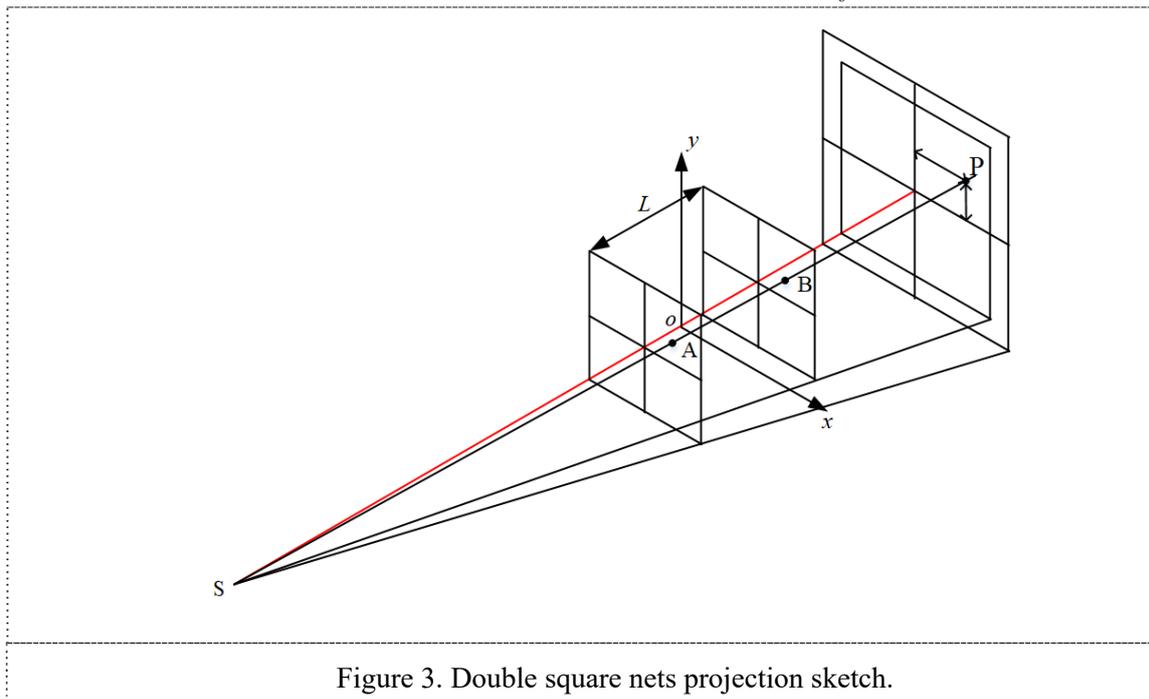


Figure 3. Double square nets projection sketch.

3.1.6. *Measurement error of characteristic points.* The measurement error of characteristic points is $\delta_x = \delta_y = \delta_z = \sqrt{\delta_0^2 + \delta_e^2 + \delta_{\Delta}^2 + \delta_4^2 + \delta_5^2 + \delta_6^2} = 0.16mm$.

3.2. *Feature point extraction error*

The space coordinates of the two characteristic points on the axis of the projectile are obtained with the cusp of the projectile is $P_1(x_1, y_1, z_1)$ and the center of the bottom of the projectile is $P_2(x_2, y_2, z_2)$. According to the error transfer model, the projectile can be obtained. In order to better analyze the attitude measurement error of projectile, it is assumed that the center of the projectile

bottom is at the origin of the world coordinate system and the yaw angle of the projectile axis is $\psi \in [0, 5^\circ]$, pitch angle is $\theta \in [0, 5^\circ]$, projectile length is 1000m. The error results obtained by using MATLAB simulation are shown in figure 4.

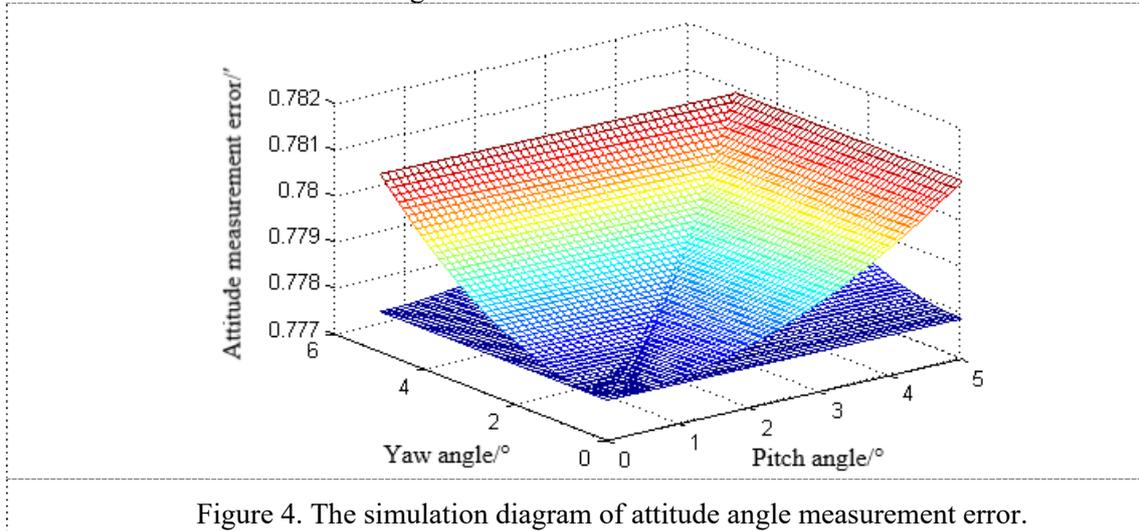


Figure 4. The simulation diagram of attitude angle measurement error.

It can be seen from the figure that when the range of projectile motion attitude is $[0, 5^\circ]$, the measurement error of the projectile's attitude is less than 0.8'.

4. Conclusion

The measurement principle and working process are studied. The motion fuzzy value of measurement system, synchronization error of flash system, camera distortion error and image feature point extraction error are analyzed. The coordinate measurement error of the measurement system characteristic point is synthesized. On this basis, the attitude measurement error of the measurement system is calculated according to the definition of attitude angle and the error transfer mechanism, and the calculation results show that the error of attitude measurement of projectile is less than 0.8'. The camera distortion error and feature extraction error are the main errors among many error factors affecting the measurement accuracy. Therefore, the camera distortion error can be controlled by the camera calibration, and the feature extraction error can be controlled by the study of sub-pixel algorithm. Therefore, the measurement error of large caliber projectile motion attitude by shadow camera method still has an improved range.

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