Error analysis of projectile attitude measurement by high-speed camera

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Abstract. Using binocular high-speed camera to capture projectile and image processing algorithm to obtain projectile attitude has become a common method. The solution accuracy of this method is very important to the process of missile-target rendezvous. In order to verify the accuracy of this method to solve the projectile attitude: I. A missile-target rendezvous attitude measurement system is built, including camera parameter calibration and data processing, and the extraction of projectile attitude parameters is realized. II. The angle measurement calibration system is built by using high-precision deflection and yaw platform and laser interferometer, and the results are compared with the built measurement system. Finally, the accuracy of this method is verified, and the error range of attitude solution is within 0.35°.

Keywords: missile-target rendezvous; binocular; high-speed camera.

1. Introduction

To evaluate the target damage effectiveness, it is urgent to accurately measure the attitude parameters of missile-target rendezvous. Most of the existing methods need to establish a fixed target to study the motion attitude of projectile at a certain position. For example, Zhang Z's binocular determination method [1] takes the left camera coordinate system (LCS) as the world coordinate system (WCS) to calibrate the internal parameters of two high-resolution cameras and the external parameters (rotation matrix and translation vector) of the right camera coordinate system (RCS) relative to the left. It is required that the calibration plate can cover the whole field of view of a single camera, but the orthogonal binocular intersection field of view is smaller than that of a single camera, which can’t meet the calibration requirements, it is also unable to solve the correct camera internal parameters. Lin Z and others analyzed the motion blur value of the measurement system, the synchronization error of the flash system, the camera distortion error and the error of image feature points for the shadow camera system for the motion attitude measurement of large caliber projectile [2, 3]. These methods aim to improve the shooting and solution accuracy of projectile through calibration, but they still can’t determine the real accuracy of projectile extraction, which hinders the application of projectile attitude in missile-target rendezvous. The fixed attitude measurement system can no longer meet the requirements of modern and highly mobile weapons and equipment [4-6]. In order to overcome the limitations of the existing attitude measurement methods, we propose a missile-target rendezvous attitude measurement method that can move with the target. The clear projectile image is obtained through non-contact measurement, and the
attitude angle of missile-target rendezvous is measured. Attitude parameter measurement of missile-target rendezvous can provide important data support and theoretical basis for target vulnerability research and weapon damage effectiveness evaluation. At the same time, it can provide theoretical and technical reference for the subsequent development of relevant mobile missile-target rendezvous attitude parameter measurement system.

2. Principle

The experimental system is mainly composed of imaging system measurement part and projectile attitude control part. The measurement part of the imaging system includes two high-resolution cameras, trigger device and computer. The projectile attitude control system used to accurately adjust the attitude angle of simulated projectile is mainly composed of simulated projectile, high-precision deflection and yaw platform, laser interferometer, mirror group and total station. The simulation experiment system can set the attitude angle of the simulated projectile, measure and calculate the attitude angle. The experimental measurement error can be calculated by comparing the experimental measurement results with the output results of laser interferometer and high-precision pan/tilt/zoom (PTZ) rotation parameters.

The simulated projectile is connected with high-precision deflection platform and yaw platform through a support. The deflection platform adjusts the pitch angle of the projectile, and the yaw platform changes the yaw angle of the projectile. In order to simulate the change of attitude angle of projectile, the mirror is installed at the tail of the simulated projectile. The laser interferometer can get the change of the attitude angle of the simulated projectile by measuring the angle change of the mirror. Limited by the fact that the laser interferometer can only measure the change of single direction angle, the following steps can be taken for the demand of simultaneously measuring the change of pitch angle and yaw angle:

1) When the pitch angle and yaw angle are both 0°, it is used as the reference zero position.
2) Make the simulated projectile rotate at a certain angle interval in a certain direction, for example, the pitch angle rotates by 2°, and take this angle as the relative zero position.
3) Adjust the direction of the mirror group of the interferometer, change the yaw angle of the simulated projectile, and the interferometer measures the change of the yaw angle. The binocular system takes pictures synchronously to obtain the simulated projectile image.
4) Then return to the relative zero position, adjust the direction of the mirror group in the interferometer, and repeat steps 2, 3 and 4 to measure different yaw angles under different pitch angles.

Based on the complexity of the operation process and the limitations of the experimental installation conditions, each adjustment of the mirror group direction of the interferometer will affect the fixation of the support to the projectile and the relative zero position, and finally affect the actual measured value of the projectile attitude angle. In order to solve this problem, the angle resolution of high-precision deflection turntable and yaw table can be calibrated while using interferometer to measure the angle change of projectile in a certain direction. For subsequent measurement of different deflection angles and yaw angles, the calibrated rotation parameters of high-precision deflection turntable and yaw table can be used as the true value of projectile attitude.

3. System construction

3.1. Angle extraction of missile-target rendezvous attitude measurement system.

After the simulation experiment system is built, the imaging system is calibrated to determine the internal and external parameters of the two cameras. Camera internal parameters describe the corresponding relationship between spatial points and imaging points in the camera coordinate system, mainly related to the camera focal length $f_x, f_y$. Camera main point $u_0, v_0$, distortion coefficient $k_1, k_2$, etc. Camera external parameters describe the relationship between camera coordinate system and external coordinate system, that is, the relationship between points in camera coordinate system and corresponding points in external coordinate system, mainly including rotation matrix R and translation vector T.
In this paper, the projectile penetration attitude angle relative to armored vehicle is required. Therefore, in WCS established with a certain position of the armored vehicle as the origin, the external parameters of the camera are the rotation matrix and translation vector relative to WCS. The coordinate system and transformation relationship involved are shown in Fig. 1.

![Figure 1. Coordinate system transformation relationship.](image)

In order to solve this problem, monocular calibration is carried out for each camera to solve its internal parameters. The calibration experiment uses a high-precision black-and-white rectangular chessboard to calibrate the internal parameters of the camera, adjust the orientation of the chessboard for many times, and take chessboard photos at different positions, angles and attitudes. In order to reduce the edge distortion and ensure the measurement accuracy, make the chessboard occupy the whole field of view as much as possible and obtain more coordinate information. The main technical parameters of the calibration plate used in this paper are as follows:

1) Overall dimension $300 \times 300\text{mm}$, single side length $30 \times 30\text{ mm}$.
2) Accuracy $\pm 0.01\text{ mm}$.

![Figure 2. Camera calibration.](image)

Before calibrating the external parameters of the camera, a calibration plate perpendicular to the projectile is placed in front of the simulated projectile as the penetration target plate of the projectile. The Leica TS60 total station is used to establish the world coordinate system at the center of the calibration plate, and then the external parameters of the two cameras are calibrated under the world coordinate system. The external parameter calibration of the camera is shown in Fig. 2 (b). The external
Parameter calibration of the camera is simpler than the internal parameter calibration. The data on a single calibration board is enough to calculate the external parameters of the camera. Measuring the high-precision coordinates of the chessboard grid in the calibration board in the world coordinate system can complete the external parameter calibration of the left and right cameras respectively. The relationship between the space point coordinates in the left and right camera coordinate system and the space point coordinates in the world coordinate system is as follows:

\[
\begin{align*}
\begin{bmatrix}
X_a \\
Y_a \\
Z_a
\end{bmatrix} &= R_l \begin{bmatrix}
X_w \\
Y_w \\
Z_w
\end{bmatrix} + T_l \\
\begin{bmatrix}
X_b \\
Y_b \\
Z_b
\end{bmatrix} &= R_r \begin{bmatrix}
X_w \\
Y_w \\
Z_w
\end{bmatrix} + T_r
\end{align*}
\] (1)

Eliminate \((X_w, Y_w, Z_w)\) of the above formula to obtain the corresponding relationship between the right camera coordinate system and the left camera coordinate system:

\[
\begin{align*}
\begin{bmatrix}
X_b \\
Y_b \\
Z_b
\end{bmatrix} &= R \begin{bmatrix}
X_a \\
Y_a \\
Z_a
\end{bmatrix} + T
\end{align*}
\] (2)

In the formula: \(T = T_r - R_r R_l^{-1} T_l\), \(R = R_r \cdot R_l^{-1}\).

The final calibration results are shown in Table 1.

| Internal and external parameters | Left camera | Right camera |
|----------------------------------|-------------|--------------|
| \((f_x, f_y)\)                   | (2364.1254, 2365.1486) | (2368.2960, 2367.8152) |
| \((u_0, v_0)\)                   | (1199.5861, 1035.7472) | (1208.5653, 1005.3394) |
| \((k_1, k_2)\)                   | (-0.0479, 0.1014)      | (-0.0475, 0.1020)      |
| \(R\)                            | \([-0.0132, 0.5377, -0.8431]\) | \([0.0335, -0.5513, -0.8336]\) |
| \(T\)                            | \([-0.9983, 0.0414, 0.0421]\) | \([0.9972, -0.0376, 0.0650]\) |

The specification of the fixed focus lens used in this system is 8mm and fine-tuning of the focal length. From the calibration results, the focal length of the left camera is (8.156mm, 8.160mm) and the focal length of the right camera is (8.170mm, 8.169mm). The actual distance between the two cameras, that is, the baseline length is 1400mm, and the baseline calibration result is 1365mm. In the experiment, the two cameras were placed vertically and photographed orthogonally, and the binocular angle calibration result was actually 85.06°. According to the calibration results of lens focal length, binocular base distance and binocular angle and the actual values, the calibration is in line with the expected results. The Re-projection error is usually used to measure the calibration accuracy, that is, the Euclidean distance between the theoretical projection point and the coordinate point obtained after the current projection. Fig. 3 shows the Re-projection error of camera calibration. It can be seen that the camera calibration accuracy does not exceed 0.5 pixels. The calibrated binocular imaging system has the function of measuring three-dimensional spatial coordinates.
The three-dimensional attitude parameters of the projectile can be obtained by digital image processing of the collected image, and the data processing part is shown in Fig. 4. This part mainly includes binocular determination, obtaining the internal and external parameters of the camera, image distortion correction, edge preserving and noise reduction, image enhancement, image segmentation, image thinning, extracting the central axis, spatial three-dimensional line reconstruction and attitude angle calculation.

3.2. Angle measurement calibration system degree acquisition
In order to verify the rotation accuracy of high-precision deflection and yaw platform, a high-precision laser interferometer is used for calibration verification. Firstly, fix the interferometer on a fixed platform and adjust the laser light path of the laser interferometer to make it work normally. Secondly, set the
rotation angle of high-precision deflection and yaw platform. The laser interferometer can calculate the rotation angle of high-precision deflection and yaw platform according to the reflector.

**Table 2.** Calibration results of high precision deflection and yaw platform.

| Set value/° | Measured value/° | Error value/° |
|-------------|------------------|---------------|
| Deflection platform | | |
| 2.00 | 2.0163 | 0.0163 |
| 4.00 | 3.9890 | -0.0110 |
| 6.00 | 6.0272 | 0.0272 |
| 8.00 | 7.9758 | -0.0242 |
| 10.00 | 9.9516 | -0.0484 |
| Yaw platform | | |
| 2.00 | 1.9827 | 0.0173 |
| 4.00 | 3.9815 | -0.0185 |
| 6.00 | 6.0189 | 0.0189 |
| 8.00 | 8.0364 | 0.0364 |
| 10.00 | 9.9531 | -0.0469 |

It can be seen from table 2 that the angular resolution of high-precision deflection and yaw platform is within 0.05 °, and the rotation parameters of deflection and yaw platform can be regarded as the true value of target missile attitude, which is convenient to set missile attitude measurement under different states.

4. Results and discussion

The error of the comparison between the angle of the test system and the angle of the turntable, and the comparison of the measurement results of the projectile attitude angle are shown in Table 3. Where $P_a$, $Y_a$, $P_e$, $Y_e$ represents the actual value of pitch angle, the actual value of yaw angle, the calculated value of pitch angle, the calculated value of yaw angle, the error value of pitch angle and the error value of yaw angle respectively.

**Table 3.** Comparison of measurement results of projectile attitude angle.

| $P_a$ /° | $Y_a$ /° | $P_e$ /° | $Y_e$ /° |
|----------|----------|----------|----------|
| 0.0019   | 2.0131   | 0.0662   | 2.2799   | 0.0643   | 0.2668   |
| 0.0019   | 4.0210   | 0.0702   | 4.1966   | 0.0683   | 0.1756   |
| 0.0019   | 5.9795   | 0.0627   | 5.6679   | 0.0608   | -0.3116  |
| 0.0019   | 7.9923   | 0.0595   | 7.7461   | 0.0576   | -0.2462  |
| 0.0019   | 9.9211   | 0.0654   | 9.6035   | 0.0635   | -0.3176  |
| 1.9852   | 0.0052   | 2.2136   | 0.0551   | 0.2284   | 0.0499   |
| 4.0325   | 0.0052   | 4.3173   | 0.0532   | 0.2848   | 0.0480   |
| 6.0342   | 0.0052   | 5.7191   | 0.0643   | -0.3151  | 0.0591   |
| 7.9864   | 0.0052   | 7.7123   | 0.0654   | -0.2741  | 0.0602   |
| 9.8915   | 0.0052   | 9.5922   | 0.0806   | -0.2993  | 0.0754   |
| 2.00     | 2.00     | 1.8909   | 1.7572   | -0.1091  | -0.2428  |
| 2.00     | 4.00     | 1.8012   | 4.3127   | -0.1988  | 0.3127   |
| 2.00     | 6.00     | 1.7645   | 6.2065   | -0.2355  | 0.2065   |
| 2.00     | 8.00     | 1.8171   | 7.168   | -0.1829  | -0.2832  |
| 2.00     | 10.00    | 1.7909   | 9.7297   | -0.2091  | -0.2703  |
| 4.00     | 4.00     | 3.7902   | 4.3078   | -0.2098  | 0.3078   |
| 4.00     | 6.00     | 3.7531   | 5.7784   | -0.2469  | -0.2216  |
| 4.00     | 8.00     | 3.6955   | 8.1376   | -0.3045  | 0.1376   |
| 4.00     | 10.00    | 3.7103   | 9.6994   | -0.2897  | -0.3006  |
| 6.00     | 8.00     | 5.7435   | 6.2016   | -0.2565  | 0.2016   |
| 6.00     | 10.00    | 6.2912   | 7.8014   | 0.2912   | -0.1986  |
| 6.00     | 10.00    | 6.3111   | 9.8102   | 0.3111   | -0.1898  |
| 8.00     | 8.00     | 7.7035   | 8.2027   | -0.2965  | 0.2027   |
| 8.00     | 10.00    | 7.7922   | 9.7538   | -0.2078  | -0.2462  |
| 10.00    | 10.00    | 9.7413   | 9.7657   | -0.2587  | -0.2343  |
In order to more intuitively analyze the error of pitch and yaw angle, the error data in Table 3 are drawn into scatter diagram as Fig. 5. From the error results, the maximum error of the pitch and yaw angle of the target solved by the algorithm in this paper is no more than 0.35 °, which can verify the correctness of the target attitude solution.

Figure 5. Distribution of attitude angle error.

5. Conclusion

Based on the research of missile-target rendezvous attitude measurement system, a static simulation measurement system is built. The pitch and yaw steering angles of the target controlled by the high-precision deflection and yaw platform are measured by laser interferometer. Compared with the results of binocular attitude measurement. The correctness of the algorithm is verified, and the error range of attitude solution is within 0.35 °. Therefore, this method can ensure that the attitude measurement system of missile-target rendezvous has high reliability and ensure that the results have practical significance in the study of parameter model of missile-target rendezvous.

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