Measurement method of projectile explosion position based on two area array CCDs intersection and its error analysis

HANSHAN LI*
School of Electronic and Information Engineering, Xi'an Technological University, Xi'an, 710021, China

Because of the difference of the reflectance characteristic of the ground target and the detonation control of the projectile fuze, the distribution of the projectile explosion position is an uncertain state in the falling process of the terminal trajectory, it is relatively difficult to obtain the parameters of projectile explosion position. Combine with the characteristics of the test environment, this paper proposes a new test and calculation method of projectile explosion position based on two area array CCDs intersection by using the standard rod as the reference object, establishes the object-image relationship calculation function of the standard rod in the CCD imaging system, and deduces the analytical model and calculation method of the projectile explosion position according to the spatial intersection of the two area array CCDs and gives test method. In addition, the paper sets up the error calculation model of projectile explosion position and analyses the influence of uncertainty error factors under the engineering uncertainty testing. Through calculation and experiment analysis, the error distribution of the test system is given, and the proposed test method and the computation model are verified.

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1. Introduction

In the weapon test range, the spatial position parameters of the projectile explosion is an important technical index to measure the performance of the artillery in terminal trajectory, it is also an important data for damage assessment of terminal ballistic target. Because of the difference of the reflectance characteristic of the ground target and the detonation control of the projectile fuze, the distribution of the projectile explosion position is an uncertain state in the falling process of the terminal trajectory, it is relatively difficult to obtain the parameters of projectile explosion position [1]. In terms of damage test of projectile explosion, Tian et al. [2] proposed an ammunition damage assessment algorithm based on fuze real-time explosion point. Also, the performance evaluation of fuze based on projectile explosion position was studied and the influence of projectile explosion position error distribution on fuze was analysed in reference [3].

About the testing method of projectile explosion position, Chen, et al. [4] proposed a five-element array algorithm based on time difference technique and studied the geometric relationship between each array elements and the calculation of parameters. Feng, et al. [5] derived the calculation function of projectile positioning by using spherical coordinate method and least square method. Dong, et al. [6] proposed a method for measuring the projectile explosion position with the combination of acoustic sensors array and optical detection. According to the signal synchronously collected by the photoelectric detector and the double triangular acoustic sensors array, Zheng, et al. [7] calculated the time interval between projectile passing through each sensor, and combined with the instantaneous parameters of the projectile explosion and the known coordinate parameters of each acoustic sensors array, the explosion position of the projectile was obtained. Based on the photoelectric detection mechanism, Li, et al. [8] established the calculation model of projectile explosion position measured by multiple sky screen intersection and single area array CCD. Besides, Dong et al. [9] proposed a method of the projetile explosion position based on the probability density of multi-array; and so on. Concerning projectile's plane coordinate test method, some experts have proposed to use the screen array. Screen array is a test equipment which is composed of screens or sky screen sensors [10-13]. These methods mainly use the time value of projectile passing through the screen array to calculate the two-dimensional coordinates of projectile, which can be calculated under the condition that the projectile dose not explode, if the projectile has exploded, the screen or sky screen array will not be able to obtain the projectile position parameters [14-15]. Therefore, these testing method still cannot solve the problem of projectile explosion position parameters testing.

With the introduction of equipment operation experience in the process of weapon assessment, the demand for military tactical drills is increasing, and the necessity of accurate obtain of projectile explosion positions is also increasing, especially for the test of the spatial coordinates of the projectile low explosion position. Due to the difference of reflection characteristics of ground target, the intensity of target reflected echo information is very different, which makes the distribution of projectile explosion position is in random. In order to improve the testing accuracy of projectile explosion position parameters, this paper proposes a test method based on two area array CCDs intersection by using the standard rod as the reference object. This paper's primary work and contributions are as follows:

(1) we propose a new test and calculation method of projectile explosion position based on two area array CCDs intersection by using the standard rod as the reference object. This testing method can avoid the influence of environmental interference target, and it directly uses the relationship between the actual size of standard rod and the size of CCD pixel to invert and calculate the explosive position of projectile.

(2) we establish the object-image relationship calculation function of the standard rod in the CCD imaging system, and deduce the analytical model and calculation method of the projectile explosion position according to the spatial intersection of the two area array CCDs and give test method.

(3) we set up the error calculation model of projectile explosion position and analyse the influence of uncertainty error factors under the engineering uncertainty testing.

2. Measurement method of projectile explosion position based on two area array CCDs intersection

According to the characteristics of the projectile fuze explosion in terminal trajectory, we use two area array CCDs to form the intersection measure method and testing system. In the testing system, in order to obtain the accurate calculation basis of projectile explosion imaging, we introduce the standard rod as the testing calibration, set up the object-image relationship of standard rod and CCDs, and determine the pixel size scaling coefficient of standard rod imaging. Fig. 1 is the testing diagram of two area array CCDs intersection by using standard rod.

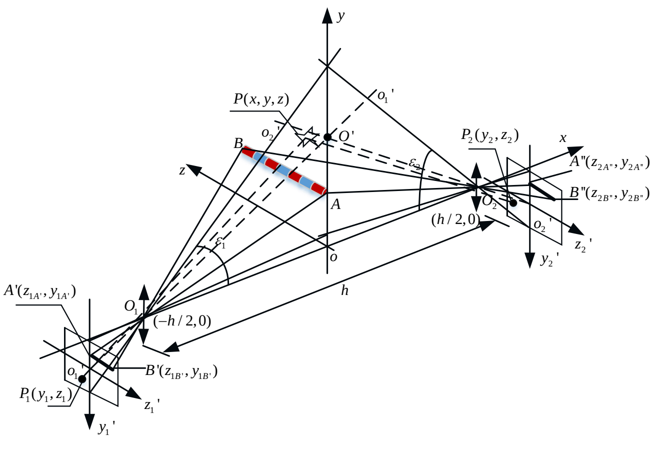


Fig. 1. The testing diagram of projectile explosion position on two area array CCDs intersection by using standard rod

In Fig. 1, the position of point O_1 and O_2 is optical lens central of CCD1 and CCD2 respectively, the coordinates of O_1 and O_2 are $(-h/2,0)$ and $(h/2,0)$, h is the distance between O_1 and O_2. O_1O' and O_2O' are the optical axes of area array CCD1 and CCD2, o is the point where O' is projected onto the ground, and o is in the middle of O_1O_2, namely, $oO_1 = oO_2$. ε_1 and ε_2 are the angles between the two optical axes and O_1O_2 respectively. In the coordinate system $oxyz$, the plane xoy is perpendicular to the horizontal trajectory.

In order to accurately obtain the position parameters of projectile explosion, we place a standard rod *AB* in the effective optical field of two area array CCDs as the reference for calculation. The length of standard rod is *L*, namely, *AB* = *L*, *A* and *B* are the two end points of the standard rod. During the testing process, the end point *A* of the standard rod is on the line oO', and standard rod is placed horizontally and perpendicular to the plane xoy. The imaging relationship was obtained by collecting the image of the standard rod. Assuming that $z_1'o_1'y_1'$ and $z_2'o_2'y_2'$ are the imaging coordinate system of CCD1 and CCD2 respectively, o_1' and o_2' are their imaging center position, which is determined by the CCD itself. A' and B' are imaging points of the end points *A* and *B* of standard rod in CCD1, A'' and B'' are imaging points of the end points *A* and *B* of standard rod in CCD2. If the number of pixels of the area array CCD camera is $n \times m$, the imaging position of o_1' is $o_1'(n/2, m/2)$ in the imaging coordinate system $z_1'o_1'y_1'$, the imaging position of o_2' is $o_2'(n/2, m/2)$ in the imaging coordinate system $z_2'o_2'y_2'$, among them, *n* and *m* are the number of pixels of the area array CCD camera in directions $o_1'z_1'$ and $o_1'y_1'$ or directions $o_2'z_2'$ and $o_2'y_2'$, the pixel size of area array CCD camera is $a \times a$. Assuming that the coordinates $A'(z_{1A'}, y_{1A'})$ and $B'(z_{1B'}, y_{1B'})$ in $z_1'o_1'y_1'$ are the imaging point A' and B' in CCD1, and the coordinates $A''(z_{2A''}, y_{2A''})$ and $B''(z_{2B''}, y_{2B''})$ in $z_2'o_2'y_2'$ are the imaging point A'' and B'' in CCD2, because the standard rod is perpendicular to the plane *xoy*, and then, $y_{1A'} = y_{1B'}$, $y_{2A'} = y_{2B'}$. In the test, we imaged the position of end point *A* of the standard rod on the $o_1'y_1'$ and $o_2'y_2'$ lines in the CCD1 and CCD2 imaging coordinate systems respectively, namely, the imaging pixel position of end point *A* of standard rod in $o_1'y_1'$ and $o_2'y_2'$ both are $m/2$, then we can get that $y_{1A'} = y_{2A'} = m/2$, $z_{1A'} = z_{2A'} = n/2$. $z_{1A'} - z_{1B'}$ and $z_{2A'} - z_{2B'}$ are the imaging lengths of the standard rod on the CCD1 and CCD2. The imaging pixel size ratio coefficient of standard rod on CCD1 and CCD2 can be calculated by formula (1).

$$\begin{cases} k_1 = \dfrac{L}{z_{1A'} - z_{1B'}} \\ k_2 = \dfrac{L}{z_{2A'} - z_{2B'}} \end{cases} \tag{1}$$

where k_1 and k_2 are the coefficients of the image in CCD1 and CCD2.

Assuming that $P(x,y,z)$ is the position of the projectile explosion, $P_1(y_1,z_1)$ and $P_2(y_2,z_2)$ are the imaging pixel position of the projectile explosion in CCD1 and CCD2. We project point $P(x,y,z)$ onto the plane *xoy*, and point $P(x,y,z)$ just represents the coordinate parameters x and y . The spatial relationship of the projectile explosion in coordinate system *xoyz* is shown in Fig. 2. Assuming that $\varepsilon_1 = \varepsilon_2 = \varepsilon$, $f_1 = f_2 = f$, f_1 and f_2 are the focal lengths of the CCD1 and CCD2 respectively. The slope of lines O_1P and O_2P can be obtained by formula (2).

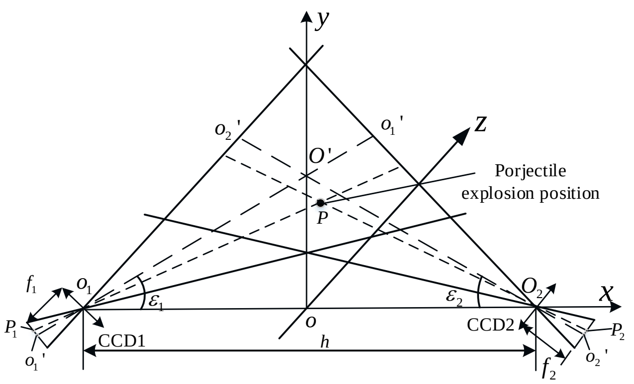


Fig. 2. The image relationship of projectile explosion point in coordinate system xoyz

$$\begin{cases} k_{O_1P} = tg[\varepsilon - arctg(y_1 - m/2)a \cdot k_1 / f] \\ k_{O_2P} = tg[\varepsilon - arctg(y_2 - m/2)a \cdot k_2 / f] \end{cases} \tag{2}$$

where k_{O_1P} and k_{O_2P} are the slope of lines O_1P and O_2P ; and then, the linear equation of O_1P can be expressed by formula (3).

$$y = k_{O_1P} \cdot (x + h/2) \tag{3}$$

And the linear equation of O_2P is

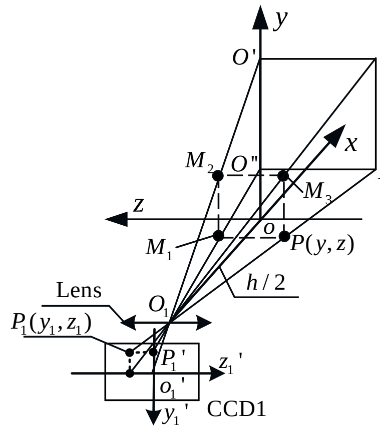
$$y = k_{O_2P} \cdot (h/2 - x) \tag{4}$$

By combining formulas (3) and (4), the coordinate parameters x and y of the projectile explosion can be obtained by formulas (5) and (6).

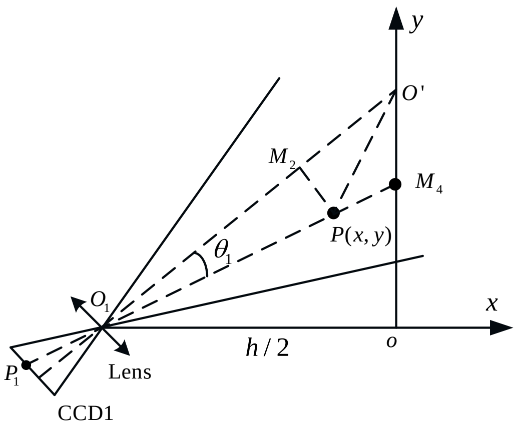
$$x = \frac{(k_{O_2P} - k_{O_1P}) \cdot h/2}{k_{O_2P} + k_{O_1P}} \tag{5}$$

$$y = k_{O_1P} \cdot h/2 \cdot (\frac{k_{O_2P} - k_{O_1P}}{k_{O_2P} + k_{O_1P}} + 1) \tag{6}$$

From the perspective of coordinate plane *yoz*, for the position $P(x,y,z)$ of the projectile explosion, the imaging coordinates z_1 and z_2 are the imaging position of the projectile explosion position in directions $o_1'z_1'$ and $o_2'z_2'$ on imaging planes of CCD1 and CCD2. They are not the actual projectile explosion coordinate parameters in direction oz , we used CCD1's imaging instructions, as shown in Fig. 3.



(a) Side view of projectile explosion image in CCD1



(b) Front view of projectile explosion image in CCD1

Fig. 3. The image relationship of projectile explosion point on plane yoz in CCD1

In Fig. 3 (a), $P_1(y_1,z_1)$ is the imaging pixel position of the projectile explosion in CCD1, o_1' is the imaging center position of CCD1, M_1 is the point where the projectile explosion position is projected onto the plane *xoy*, $O"$ is intersection point between O_1M_1 and oO'. Plane $O'O"M_4M_5$ is on plane *yoz* and perpendicular to plane xoy. The number of imaging pixels of P_1P_1' is $z_1 - n/2$. According to imaging relationship of CCD1, we obtain the length of $O"M_4$, $O"M_4 = a \cdot k_1(z_1 - n/2)$, $O"M_4$ is not the actual coordinate value of *z*.

To get the actual coordinate value of *z*, we see the projectile explosion point from the view of plane *xoy*, as shown in Fig. 3(b), and find point M_4 is not real point P. According to Fig. 3 (a), the angle of $\angle O'O_1M_5$ can be obtained by formula (7).

$$\tan \angle O'O_1M_5 = \frac{a \cdot k_1(z_1 - n/2)}{\sqrt{OO'^2 + (h/2)^2}} = \frac{a \cdot k_1(z_1 - n/2)}{\sqrt{0.5h \cdot \tan\varepsilon_1 + (h/2)^2}} \tag{7}$$

In Fig. 3(b), θ_1 is the angle between the optical axis O_1O' of CCD1 and O_1P. The formula (8) is its calculation function.

$$\theta_1 = arc\tan[(y_1 - m/2)a \cdot k_1 / f] \tag{8}$$

By combining formulas (5) and (6), the length of O_1M_2 can obtained by formula (9).

$$O_1M_2 = \cos\theta_1 \cdot \sqrt{(0.5h - x)^2 + (0.5h \cdot \tan\varepsilon_1 \text{-} y)^2} \tag{9}$$

Since $z = M_1P = M_2M_3$, according to triangle $\Delta O_1M_2M_3$, and then, the actual coordinate value of *z* can be obtained by formula (10).

$$\begin{aligned} z &= O_1M_2 \cdot \tan\angle O'O_1M_5 \\ &= \cos\{\arctan[(y_1 - m/2)a \cdot k_1 / f\} \cdot \sqrt{(0.5h - x)^2 + (0.5h \cdot \tan\varepsilon_1 \text{-} y)^2} \\ &\times \frac{a \cdot k_1(z_1 - n/2)}{\sqrt{0.5h \cdot \tan\varepsilon_1 + (h/2)^2}} \end{aligned} \tag{10}$$

In the same way, we can also obtain actual coordinate value of *z* based on CCD2's projectile explosion imaging principle.

On basis of formulas (5), (6) and (10), the position $P(x, y, z)$ of the projectile explosion is determined.

Regarding the layout method and steps of the standard rod, first, the standard rod has the function of horizontal calibration, which can determine that the position of the designated point of the standard rod is at the centre of the image of the two area array CCDs through the arrangement position of the standard rod; For example, the end point *A* of the standard rod can be at the imaging centre of the area array CCD in Fig. 1. Second, after the central imaging position is determined, we adjust the standard rod and make it image on the CCD imaging surface, so that the standard rod is in a horizontal state in the CCD imaging. Third, we collect the information of standard rod before the test, determine the imaging position of standard rod and its imaging pixels through the image processing algorithm, and calibrate the actual size of each image pixel corresponding to the image pixel of standard rod in the test. Fourth, after the first three processing steps are completed, we withdraw from the standard rod. When the image position information of the projectile explosion is captured in the test, the actual position of the projectile explosion is calculated according to the calibrated information and the calculation model of the projectile explosion position.

3. Uncertainty analysis of measurement error

According to the calculation model of projectile explosion position based on two area array CCDs intersection, the main factors affecting the measurement of projectile explosion position are the distance between point O' and o, which is recorded oO' as *S*, namely, $oO' = S$, the distance between the two area array CCD cameras, the image two-dimensional coordinate of projectile explosion position, and the angles between the two optical axes and O_1O_2. Ideally, the error of test results caused by the manufacturing parameters of area array CCD is ignored, and the coordinate measurement uncertainty function can be expressed by formula (11).

$$\begin{cases} x = f_x(S, h, \varepsilon_1, \varepsilon_2, z_i, y_i) \\ y = f_y(S, h, \varepsilon_1, \varepsilon_2, z_i, y_i), i = 1, 2 \\ z = f_z(S, h, z_i, y_i) \end{cases} \tag{11}$$

where the measurement uncertainty functions of three-dimensional coordinates are expressed as f_x, f_y, f_z, each component in an uncertainty function is independent of each other [16-17]. In the ideal model, the measurement uncertainty functions are expressed by formula (12) to (14).

$$u(x) = \left[\sum_{u=1}^{2}\left[\frac{\partial x}{\partial S}\right]^2 2u^2(S) + \sum_{u=1}^{2}\left[\frac{\partial x}{\partial h}\right]^2 2u^2(h) + \sum_{u=1}^{2}\left[\frac{\partial x}{\partial \varepsilon_1}\right]^2 u^2(\varepsilon_1)\right] + \left[\sum_{u=1}^{2}\left[\frac{\partial x}{\partial \varepsilon_2}\right]^2 u^2(\varepsilon_2) + \sum_{u=1}^{2}\left[\frac{\partial x}{\partial z_i}\right]^2 u^2(z_i) + \sum_{u=1}^{2}\left[\frac{\partial x}{\partial y_i}\right]^2 u^2(y_i)\right] \tag{12}$$

$$u(y)=\left[\sum_{u=1}^{2}\left[\frac{\partial y}{\partial S}\right]^2 2u^2(S)+\sum_{u=1}^{2}\left[\frac{\partial y}{\partial h}\right]^2 2u^2(h)+\sum_{u=1}^{2}\left[\frac{\partial y}{\partial \varepsilon_1}\right]^2 u^2(\varepsilon_1)\right]+\left[\sum_{u=1}^{2}\left[\frac{\partial y}{\partial \varepsilon_2}\right]^2 u^2(\varepsilon_2)+\sum_{u=1}^{2}\left[\frac{\partial y}{\partial z_i}\right]^2 u^2(z_i)+\sum_{u=1}^{2}\left[\frac{\partial y}{\partial y_i}\right]^2 u^2(y_i)\right] \tag{13}$$

$$u(z)=\left[\sum_{u=1}^{2}\left[\frac{\partial z}{\partial S}\right]^2 2u^2(S)+\sum_{u=1}^{2}\left[\frac{\partial z}{\partial h}\right]^2 2u^2(h)+\sum_{u=1}^{2}\left[\frac{\partial z}{\partial x_i}\right]^2 u^2(x_i)+\sum_{u=1}^{2}\left[\frac{\partial z}{\partial y_i}\right]^2 u^2(y_i)\right] \tag{14}$$

Due to the different sources and independent of each other, the measurement uncertainty of x coordinate, y coordinate and z coordinate in target plane is different. Within the range of the selected test target plane, the measurement uncertainties of x coordinate, y coordinate and z coordinate of each impact point are comprehensively, which is considered as the evaluation function [18] of the uncertainty of projectile coordinate in the whole test area, we use the formula (15) to express this function.

$$\Delta u=\frac{\sum\sqrt{\delta x^2(j,k)+\delta y^2(j,k)+\delta z^2(j,k)}}{j\times k} \tag{15}$$

where $\delta x(j,k)$, $\delta y(j,k)$ and $\delta z(j,k)$ are the uncertainties of the three-dimensional coordinates of the explosion position respectively; (j,k) is the coordinate of the standard rod relative to the actual explosion position.

3.1. Analysis of the uncertainty in ideal condition

There are many factors affecting the uncertainty of coordinate measurement in ideal conditions. Among them, the distance S, the distance between the two area array CCD cameras, the image two-dimensional coordinate of projectile explosion position, and the angles ε_1 and ε_2. These errors can be calibrated and corrected before the test. The standard uncertainty component can be expressed by formula (16).

$$u(x,y,z)=s(\overline{x},\overline{y},\overline{z})=\frac{s(x,y,z)}{\sqrt{j\times k}} \tag{16}$$

where $s(\overline{x},\overline{y},\overline{z})$ is the ideal standard value of the explosion position, $s(x,y,z)$ is the actual measured value of the explosion position. The coordinate measurement uncertainty in the ideal test model is calculated under the influence of various factors. It can be seen that in the ideal condition, when the influence of the actual project is ignored and the position of $s(\overline{x},\overline{y},\overline{z})$ the standard rod relative to the projectile explosion position is ideal, the uncertainty of the measured spatial coordinates of the explosion position in x,y,z direction basically presents a linear change. When the position of the end point of the standard rod relative to the projectile explosion position changes, the uncertainty of the projectile coordinate increases, that is, the measurement error increases. The error range is 0.02 m-0.91 m.

3.2. Analysis of the uncertainty in engineering model

In the engineering model, the projectile explosion position is uncontrollable, the position of the actual explosion position relative to the end point of the standard rod is more random, which leads to the error. Considering the factors of the distance between point O' and o, the distance between the two area array CCD cameras, and the angles between the center points of two lens and the horizontal line, we expand the calculation model of projectile explosion position to analysis the influence on the measurement results in practical engineering [19-20]. According to the influence of practical engineering on measurement results, the error of test model under three factors is considered respectively. Based on explosion position parameters obtained by the test model before expansion, the influence of various factors on the measurement uncertainty under the engineering model is analyzed. The comprehensive uncertainty can be obtained by formula (17).

$$u(x,y,z)=\frac{(s(x,y,z)\cdot S)^2+(s(x,y,z)\cdot\eta)^2+(s(x,y,z)\cdot h)^2}{\sqrt{j\times k}} \tag{17}$$

where η is the angle between the optical axes of two area array CCDs.

Before the test, it is necessary to calibrate the position of the standard rod and measure the distance from the end point of the standard rod to the horizontal plane. However, it is difficult to ensure that the actual measurement value is consistent with the theoretical value, which brings errors to the test results. Fig. 4 shows the distribution of coordinate error uncertainty under the distance deviation between the intersection point of two area array CCDs and the intersection point projected to the ground. It can be seen that when the distance deviation between the intersection point of two area array CCDs and the intersection point projected to the ground relative to the projectile explosion position is 1 m, the uncertainty is the smallest.

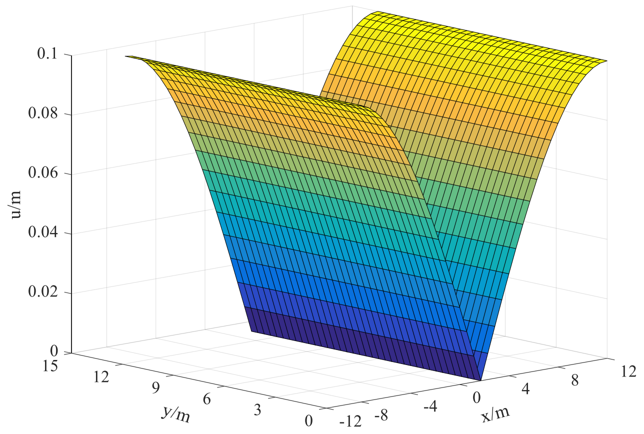


Fig. 4. Distribution of coordinate error uncertainty under the distance deviation between the intersection point of two CCDS and the intersection point projected to the ground (color online)

According to the test model of projectile explosion position based on the intersection of two area array CCDs, the angle ε_1 and ε_2 between the optical axes of the two area array CCDs and the horizontal line are consistent. However, it is difficult for these angles to achieve completely consistent in the actual test.

Fig. 5 shows the measurement uncertainty distribution when the angle between the optical axis of two area array CCDs and the horizontal line is inconsistent. When the distance deviation between the intersection point of two area array CCDs and the intersection point projected to the ground relative to the projectile explosion position is 2 m in the x direction, it can be seen the minimum measurement uncertainty is 0.036. With the distance between point O' and o relative to the projectile explosion position increases, the uncertainty of coordinate measurement increases, and the maximum measurement uncertainty is 0.092 m.

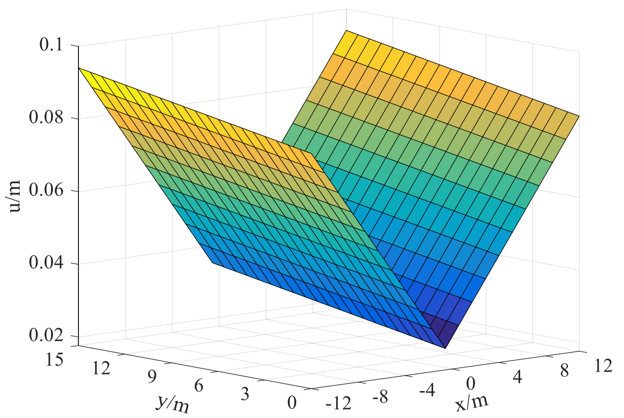


Fig. 5. Distribution of coordinate error uncertainty when the angle between the optical axis of two area array CCDs and the horizontal line is inconsistent (color online)

Fig. 6 shows the measurement error uncertainty distribution under the different distance of two area array CCDs. When the position of intersection point of two area array CCDs and the intersection point projected to the ground relative to the projectile explosion position is 3 m in the y direction, it can be seen the minimum measurement uncertainty is 0.002. It can be seen that the distance between the actual projectile explosion position and intersection point of two area array CCDs in the y direction is gradually increasing, the uncertainty of coordinate measurement is gradually increasing, and the uncertainty error range is 0.002-0.097 m.

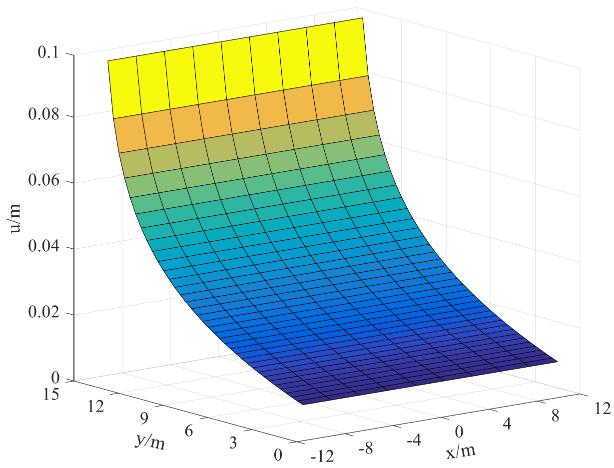


Fig. 6. The measurement error uncertainty distribution under the different distance of two area array CCDs (color online)

4. Test and analysis

In order to verify the scientific and correctness of the testing model, two area array CCDs are selected, they respectively transmit information with the data acquisition and calculation module. And the experimental conditions are as follows: the intersection area between the gun firing point and the two area array CCDs is 860 m, the height of the standard rod from the ground is 3.5 m, the length of the standard rod is 2.5 m, its diameter is 0.2 m, the angle between the area array CCD and the ground is 25.1°, the field of view of area array CCD is 63°, and the effective detection area is $15.5m \times 15.5m$.

In the experiment, the external trigger synchronous trigger command is used to obtain the image of the shot explosion point. Because the CCD acquisition needs a certain exposure time, the image area of the projectile explosion on the CCD sensitive surface is large. In order to accurately calculate the projectile explosion position, the image of the projectile explosion position collected by CCD is processed by edge detection. Before the experiment, the actual spatial coordinates of the end point of the standard rod and the coordinates of the imaging pixels can be measured by calibrating the standard rod. The two area array CCDs are connected with the data acquisition instrument through the data transmission line, and the data acquisition instrument is connected with the fire light trigger and the computer through the data transmission line. The fire trigger triggers two area array CCDs to collect the projectile explosion images of the same frame simultaneously. Matching the projectile explosion images of two area array CCDs in time sequence and processing the data by computer, and according to formulas (5), (6) and (10), the actual projectile explosion position in space is obtained. At the same time, we conduct comparative tests using the array of five acoustic sensors as the comparison, the test principle of the array of five acoustic sensors is shown in references [4] and [5].

Use the above two test methods to measure the projectiles explosion position. Among them, the coordinates of the explosion position measured by the optical intersection method of the two area array CCDs are expressed as (x, y, z), and the coordinates of the projectile explosion position measured by the array of five acoustic sensors are expressed as (x_d, y_d, z_d), and $(|\Delta x|, |\Delta y|, |\Delta z|)$ is the difference of coordinates of the explosion position measured by the two methods. Table 1 shows the measurement data.

Table 1. Measurement data under two kind of test methods

No	Two area array CCDs intersection $(x, y, z)/m$	Five-element acoustic sensors array $(x_d, y_d, z_d)/m$	error $(\lvert\Delta x\rvert, \lvert\Delta y\rvert, \lvert\Delta z\rvert)/m$
1	(-11.07,12.02, 13.60)	(-10.75,11.68, 13.29)	(0.32,0.34,0.31)
2	(-10.03,12.30, -12.12)	(-9.75,12.46, -12.35)	(0.28,0.16,0.23)
3	(-10.53,12.22, 10.82)	(-10.87,11.61, 10.59)	(0.34,0.61,0.24)
4	(11.88,13.09, 12.08)	(11.46,13.41, 12.33)	(0.42,0.32,0.25)
5	(-10.80,11.47, -11.49)	(-10.56,10.68, -11.78)	(0.24,0.21,0.29)
6	(11.54,9.25, 12.03)	(11.81,9.47, 11.79)	(0.27,0.22,0.24)

Due to the delay of sound transmission when obtain the projectile explosion signal by acoustic sensor array, the test position of five-element acoustic sensors array is located before the actual explosion position. That is, the explosion position obtained by five-element acoustic sensors array is not the actual projectile explosion position. It can be seen form Table 1 that the average deviation of the explosion position measured by the five-element acoustic sensors array and the intersection of two area array CCDs is 0.33 m in the *x*-axis direction, 0.37 m in the *y*-axis direction and 0.26 m in the *z*-axis direction. The reason why the theoretical difference between the two methods is greater than the theoretical calculation value is that the measured parameters of the array of five acoustic sensors have not been modified. Through the comparison of experimental data, we can find that the two area array CCDs intersection test method is more accurate than the five-element acoustic sensors array test method, and the average error is less than 0.32 m.

5. Conclusions

In order to further meet the needs of the projectile explosion position test in the exterior trajectory of the weapon range, this paper proposes a method for measuring the three-dimensional coordinates of the projectile explosion position based on the two area array CCDs intersection. This testing method can avoid the influence of environmental interference target, and directly uses the relationship between the actual size of standard rod and the size of CCD pixel to invert and calculate the explosive position of projectile. Two area array CCDs and a standard rod are arranged in the test site, and the optical axes of the two area array CCDs intersect at the end point of the standard rod. According to the relationship of image position between the two area array CCDs and the end point of the standard rod, the two-dimensional coordinates of the vertical direction of the projectile explosion position are calculated. Combined with the spatial geometric relationship of the side direction and the obtained two-dimensional coordinates, the calculation method of the three-dimensional coordinates of the projectile explosion position is derived. In addition, the error uncertainty of the measurement results of the projectile explosion position is derived by the uncertainty analysis method. And the influence of various factors to the uncertainty is analysed based on the ideal model and the engineering model respectively. Through the comparison between the proposed method in this paper and the acoustic sensors array method, the results show that the average deviation of the three-dimensional coordinates of the explosion position measured by these two methods is 0.27 m.

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*Corresponding author: lihanshan269@163.com