Warhead fragment spatial position acquisition and reconstruction method based on micro lens array imaging mechanism

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Aiming at the difficulty of obtaining warhead fragment spatial position information, this paper combines the four-dimensional information of the light field camera, and proposes the warhead fragment spatial position analysis and reconstruction modeling based on the micro lens array imaging mechanism. According to the relation of the main lens plane, micro lens array plane and imaging sensor plane of the light field camera, combining with the light propagation characteristics formed by the warhead fragments in the internal structure, the reconstruction model of the light field imaging warhead fragments and the calculation function of the warhead fragments on the refocused image surface is derived. Based on the relationship between the coordinates of the main lens plane and the imaging sensor coordinates of the light field camera, the analytical model of the warhead fragment spatial position is established by inversion. Through the simulation test, the imaging images of simulative multiple warhead fragments are collected, according to the inherent parameters of the light field camera and the theoretical model established, it is verified that the theoretical method can calculate the warhead fragment spatial position.

(Received March 17, 2021; accepted August 16, 2021)

Keywords: Light field camera, Micro lens array, Warhead fragment, Refocus, Inversion

1. Introduction

The dispersion and scattering characteristic parameters of the warhead fragment are important indicators to measure the damage power of weapons and ammunition. The scattering attitudes of the warhead fragments produced by the projectile explosion is different, and the volume and mass of the warhead fragments are also different, so the warhead fragments form a random and uncertain state in flight, which is difficult to accurately obtain the dynamic parameters of warhead fragments. The existing photoelectric test methods which can test the attitude, velocity and spatial position coordinates of projectile cannot meet the testing requirements of random scattering warhead fragment. At present, the test technology of the dynamic parameters of projectiles measured outside the weapon include: line CCD intersection test technology [1-2], multiple detection screen intersection test technology [3-5], laser detection screen test technology [6], etc. Because the projectile is a regular target, the existing photoelectric test methods are relatively easy to detect the regular projectile and to obtain the mathematical calculation model of projectile parameters, but it is relatively difficult to obtain the irregular warhead fragment dispersion parameters formed by the projectile explosion. The characteristics of scattering warhead fragments are: uneven volume, large dispersion range, inconsistent velocity, etc. For the array line CCD intersection test system and multiple detection screen intersection test system, the simultaneous appearance of multiple warhead fragments will interfere with the recognition and matching of the test system, such as: the double line CCD intersection test method. Line CCD is a sensor with two-dimensional information, that is, in photosensitive surface of each line CCD, there is time and space information. According to the space and time information of each line CCD, a straight-line equation between the warhead fragment spatial position and the line CCD arrangement position can be constructed. The position of the warhead fragment in the detection plane can be calculated by using two linear functions of single warhead fragment spatial position and two-line CCD arrangement position. When two warhead fragments reach its imaging detection plane, the solution function has four linear equations, resulting in two false coordinates of warhead fragment. If the number of warhead fragments increases, the number of linear equations of the calculation function increases and the false coordinates of the warhead fragments increase, making it difficult for the test system to recognize the real warhead fragment position. Multiple detection screen intersection test method is mainly to use multiple detection screens, according to a certain spatial geometric structure of these detection screens, the analytical model of the projectile parameters is established by using the time values of the projectile passing through the detection screens. This analytical model is more advantageous for the calculation of projectile parameters with a certain flight law, but when uncertain dispersion warhead fragments pass through the multiple detection screens intersection array, each detection screen may miss the detection of the warhead fragments, which making this function analysis model of this method calculate many unreal fragment parameters. For the testing of warhead fragment dynamic parameters, the existing methods mainly focus on the velocity of warhead fragment in a small detection area. For example, active detection screens array test method is introduced to measure the velocity of warhead fragment after projectile static explosion, and established 12 groups of active six detection screens array centered on the static explosion position of the tested ammunition, used the time values of the warhead fragments passing through any group of detection screens array to calculate the velocity of the warhead fragments [7]; the flight velocity and flight attitude of warhead fragments under a certain regular warhead fragment flight attitude is obtained by using six light screens target combination array, and deduced the velocity attenuation coefficient and calculation function of warhead fragments [8]; divided screen array measurement method of projectile-curtain parameter for multi-barrel volleyed weapons is studied [9]; the calibrating method of sky screen target geometric relationship and the velocity of warhead fragment is researched [10] etc. These test methods are all focused on the testing of the velocity of warhead fragments, and no scientific calculation analysis model is given for the warhead fragments spatial position. For the damage assessment of weapon smart ammunition, the velocity and dispersion parameters of warhead fragments are still the core indicators of damage assessment. But it is difficult to give a comprehensive damage effect of smart ammunition only from the velocity of warhead fragment. The parameters of penetration position, penetration dispersion density and warhead fragment attitude need to be considered comprehensively from the warhead fragment spatial position. In order to objectively evaluate the damage effect formed by warhead fragment group, this paper introduces light field imaging technology, and relies on the spatial four-dimensional information of light field imaging to establish analytical models of multiple warhead fragment spatial positions.

2. Light field imaging mechanism and reconstruction method of warhead fragment

2.1. Light field imaging mechanism of warhead fragment

The concept of light field is used to describe the three-dimensional radiation characteristics of light propagation in space. According to the light field rendering theory of Levoy, any light in space can be represented by a radiation function, which contain two-dimensional position information (u,v) and two-dimensional direction information (θ,γ), and light field and the total of radiation functions of all rays in space. Meantime, the four-dimensional information expressed by the two-dimensional direction information and the two-dimensional position information contained by the light can be parameterized by two parallel planes, as shown in Fig. 1. The light of light beam a_1a_2 is directed to the image sensor through the main lens, and its position on the main lens plane is (u,v), the position on the image sensor is (x',y'), and the distance between the main lens and the image sensor is d, which can be expressed by a four-dimensional light field function $L_d(x',y',u,v)$.

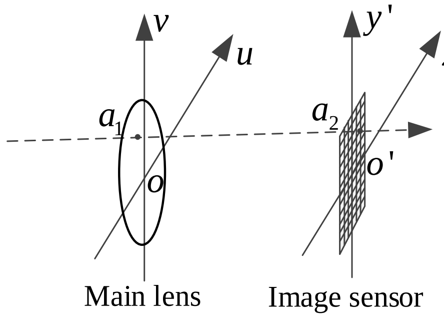

Fig. 1. The relationship between the main lens and the imaging sensor in light field

According to the light field imaging function, the image irradiance from the main lens to a certain position on the imaging sensor plane can be expressed by the integral formula of the light from the main lens:

$$E_d(x,y)=\frac{1}{d^2}\iint L_d(x',y',u,v)\cos^4\theta dudv \quad (1)$$

The light field camera inserts a micro lens array into the front end of the image sensor to record the four-dimensional information (x',y',u,v) of the light. In the light field camera, the main lens focuses on the micro lens array, and the distance from the micro lens to the image sensor is equal to the focal length of the micro lens [11]. When the image is reduced, the image is no different from the image taken by a traditional camera, but if the image is zoom in, the light spot formed by each micro lens is found, that is, the macro pixel. The position of each macro pixel determines the coordinates of the light (x',y'), and the relative position of each pixel in the macro pixel indicates the coordinates of its corresponding light (u,v). It can be seen that the size of single micro lens determines the spatial sampling resolution.

Combining the imaging mechanism of the light field camera, the micro lens array of light field camera is used to obtain the light field information of the warhead fragments by collecting the light field information of the projectile explosion scene. As shown in Fig. 2, after the projectile explodes, warhead fragments trajectories in different directions are produced. Suppose $P_i(x_i, y_i)$ is a point on the $oxyz$ coordinate system of the i-th warhead fragment, the contour points of warhead fragment at the position $P_i(x_i, y_i)$, which all pass through different (u_i, v_i) on the aperture plane from this point to the same point (k_i, h_i) on the same micro lens. After the action of the micro lens array plane of the light field camera, these points reach different sensor positions (x_i', y_i') respectively. Then the coordinates (k_i, h_i) of the micro lens and the warhead fragment point (x_i, y_i) are conjugate, recording the spatial information of the light, (u_i, v_i) and (x_i', y_i') are conjugate, recording the direction information of the light. Therefore, the warhead fragment space point light can be recorded as $L_d(x_i, y_i, u_i, v_i)$ or $L_d(h_i, k_i, x_i', y_i')$, that is, the four-dimensional light field record corresponding to the warhead fragment and the image sensor, and the warhead fragment spatial position is resolved based on the recorded light.

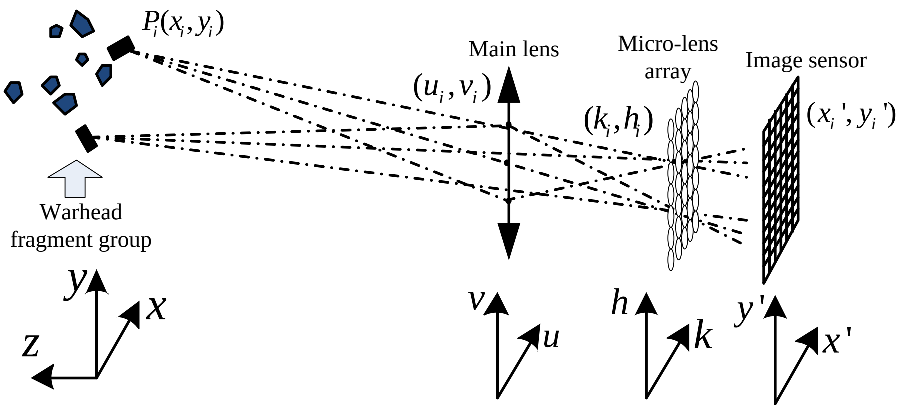

Fig. 2. Four-dimensional light field mapping model of warhead fragments

According to Fig. 2, the radiation amount of warhead fragments received on the image plane of the image sensor is expressed as:

$$E_d(x_i', y_i') = \frac{1}{d^2} \iint L_d(x_i, y_i, u_i, v_i) A(u, v) \cos^4 \theta dudv \quad (2)$$

where, θ is the angle between the light $L_d(x_i, y_i, u_i, v_i)$ and the normal of surface (u, v), and $A(u, v)$ is the pupil function [12-13].

2.2. Light field imaging reconstruction modeling of warhead fragment

According to the light field imaging mechanism of the warhead fragment, the warhead fragment light is refocused to a new imaging plane, as shown in Fig. 3. Assuming that the distance between the refocusing plane and the micro lens array plane is d', and $d' = ad$, the light L_d passing through the point (x_i', y_i') on the image plane d is $L_d(x_i', y_i', u_i, v_i)$, when focusing at the distance d' from the pupil plane, suppose the projection point coordinates of the light $L_{d'}$ refocusing plane is (x'', y''), the light field at (x'', y'') can be expressed as $L_{d'}(x_i'', y_i'', u_i, v_i)$.

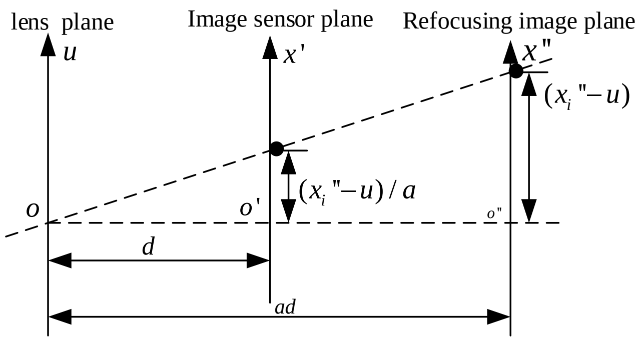

Fig. 3. Principle of digital refocusing of light field imaging

The intersection coordinates of $L_{d'}$ on the image sensor plane is $(u_i + (x_i' - u)/a, v_i + (y_i' - v)/a)$, the lights L_d and $L_{d'}$ are the same light, and the two coordinates have a relationship of formula (3).

$$\begin{aligned} L_{d'}(x_i", y_i", u_i, v_i) &= L_d(u_i, v_i, u_i + (x_i"-u)/a, v_i + (y_i"-v)/a) \\ &= L_d(u_i, v_i, u_i(1-1/a) + x_i"/a, v_i(1-1/a) + y_i"/a) \end{aligned} \tag{3}$$

Combining formulas (3) and (2), it is:

$$\begin{aligned} &E_{d'}(x", y") \\ &= \iint L_d(u_i, v_i, u_i(1-1/a) + x_i"/a, v_i(1-1/a) + y_i"/a) A(u,v) \cos^4\theta dudv \end{aligned} \tag{4}$$

By changing the position parameter a of formula (3), the clear image on the image surface of different warhead fragment spatial positions can be calculated. The function of the warhead fragment imaging in the refocusing image plane obtained by formula (4) can be inversely calculated the three-dimensional position of the warhead fragment in the light field camera.

3. Calculation modeling of warhead fragment position of light field imaging

From the four-dimensional light field information of the light field camera, the coordinate position of the main lens plane (u_i, v_i), and the coordinate position of the imaging sensor plane (x_i', y_i'), the point-direction formula of the light equation of the i-th warhead fragment can be obtained as [14-15]:

$$\frac{x-u_i}{x'-u_i} = \frac{y-v_i}{y'-v_i} = \frac{z}{d} \tag{5}$$

The general formula of changing into a straight line is as follows:

$$\begin{cases} (x_i'-u_i)x - (y_i'-u_i)y = (x_i'-v_i)u_i + (y_i'-u_i)v_i \\ dx - \dfrac{(x_i'-u_i)}{d} z = du_i \end{cases} \tag{6}$$

That is:

$$\begin{cases} A_{i1}x + B_{i1}y + C_{i1}z + D_{i1} = 0 \\ A_{i2}x + B_{i2}y + C_{i2}z + D_{i2} = 0 \end{cases} \tag{7}$$

where, $A_{i1} = x_i'-u_i$, $B_{i1} = -y_i'+u_i$, $C_{i1} = 0$, $D_{i1} = -(x_i'-v_i)u_i - (y_i'-u_i)v_i$; $A_{i2} = d$, $B_{i1} = 0$, $C_{i2} = \dfrac{-x_i'+u_i}{d}$, $D_{i2} = -du_i$.

When the warhead fragments are captured by n micro lenses at the same time, the joint equations can be established through multiple micro lens [16]:

$$MN = D \tag{8}$$

where, the matrix M , the vector N and the vector D are:

$$M = \begin{pmatrix} A_{11} & B_{11} & C_{11} \\ \vdots & \vdots & \vdots \\ A_{n2} & B_{n2} & C_{n2} \end{pmatrix} \tag{9}$$

$$N = [x_i, y_i, z_i]^T \tag{10}$$

$$D = (-D_{11}, -D_{12}, \cdots, -D_{n1}, -D_{n2}) \tag{11}$$

Formula (8) is the hyper-deterministic formula, and the least square method is used to calculate the approximate solution of the hyper-deterministic formula. If the residual error of (8) are $R = D - MN$ and $M^T R = 0$, then:

$$M^T D - M^T MN = 0 \tag{12}$$

$$(M^T M)N = M^T D \tag{13}$$

When the rank of M is equal to 3, the matrix $M^T M$ is a full rank, so the unknown N has a unique solution, and the spatial position $P(x_i, y_i, z_i)$ of the i-th warhead fragment can be obtained:

$$\begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} = (M^T M)^T M^T D = \left[\begin{pmatrix} A_{11} & \cdots & A_{n2} \\ B_{11} & \cdots & B_{n2} \\ C_{11} & \cdots & C_{n2} \end{pmatrix} \begin{pmatrix} A_{11} & B_{11} & C_{11} \\ \vdots & \vdots & \vdots \\ A_{n2} & B_{n2} & C_{n2} \end{pmatrix} \right]^T \begin{pmatrix} A_{11} & B_{11} & C_{11} \\ \vdots & \vdots & \vdots \\ A_{n2} & B_{n2} & C_{n2} \end{pmatrix}^T (-D_{11}, -D_{12}, \cdots, -D_{n1}, -D_{n2}) \tag{14}$$

4. Calculation and experimental analysis

According to the analysis and reconstruction modeling of spatial position of warhead fragment based on the light field camera, it is necessary to determine the parameters of the light field camera before obtaining the spatial position information of each warhead fragment. It can be known from the theoretical model that we need to consider the distance parameter between the main lens and the photosensitive plane of the image sensor, the resolution of the image sensor and the size of the unit micro lens to improve the accuracy of the spatial position information of warhead fragment. This experiment uses a light field camera of Lytro with 11 million effective pixels. The pixel level is 10 to 12 million, the pixel of the image sensor is 1024×1024, the focal length of the main lens is variable, the zoom range is 35-280 mm, the maximum aperture is 1:2, and the sampling rate is 0.2ms.

In order to obtain clear imaging quality of warhead fragment, the parameter between the refocusing plane and the image sensor plane is the core. Therefore, the radiation energy of the warhead fragment on the photosensitive surface of the image sensor need be calculated, and the imaging energy of the warhead fragment reflects the reconstruction accuracy of the depth surface of the warhead fragment at different positions. The main steps of the calculation method are:

(1) An image with multiple warhead fragments through a light field camera is captured, and the pixel position of warhead fragment of the image sensor on the image plane (x_i', y_i') is obtained by an image processing algorithm;

(2) The coordinate (u_i, v_i) and parameters a and d of the lens plane are determined according to the inherent parameters of the light field camera;

(3) According to formulas (5), (6) and (7), A_{ij}, B_{ij}, C_{ij} and D_{ij}, $i=1,2,\cdots,n$, $j=1,2$ are calculated;

(4) According to the calculation results of steps (1)-(3), M and D are calculated;

(5) According to formula (14), N is calculated, that is the spatial position of the i-th warhead fragment $P(x_i, y_i, z_i)$.

According to the above calculation steps, we use the simulated device to launch simulated small warhead fragments in indoor. The velocity of simulated warhead fragment is about 30-60m/s. The simulated warhead fragments are regular, and the designed light field test target surface is $1.5m\times1.5m\times1m$. In order to enhance the contrast of the simulated small warhead fragments in space, an infrared laser is arranged on the same side as the light field camera to illuminate the simulated small warhead fragments. The purpose is to improve recognition the small warhead fragments. Fig. 4 is the schematic diagram of test. The cube object is used in the experiment, and its size is $0.1m\times0.1m\times0.1m$, according to the principle of light field imaging, each pixel of a cube object on the imaging plane represents 8.5 mm.

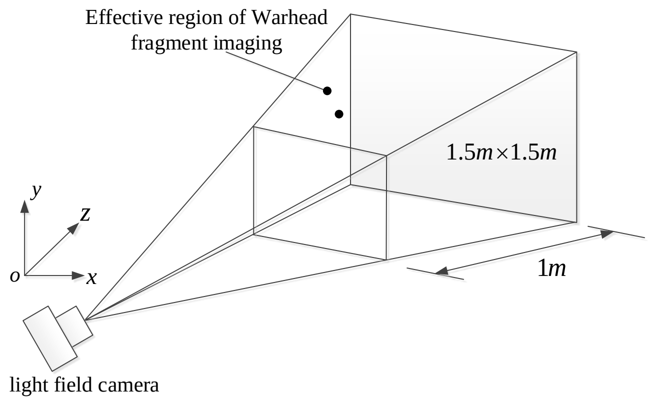

Fig. 4. The schematic diagram of test

Figs. 5 and 6 show the simulated small warhead fragments captured by the two groups. According to the above calculation method, the spatial position of the simulated small warhead fragment is shown in Tables 1 and 2.

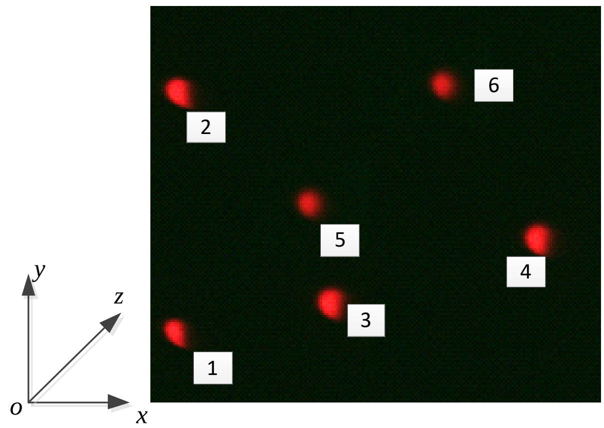

Fig. 5. The first group of simulated small warhead fragment images (color online)

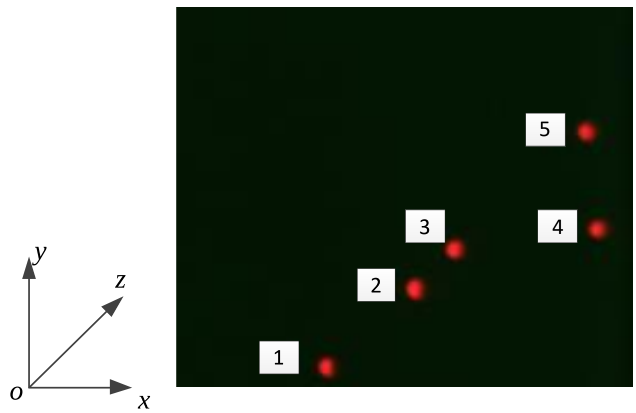

Fig. 6. The second group of simulated small warhead fragment images (color online)

Table 1. The calculation results of the spatial position of the first group of simulated small warhead fragment

NO.	*x*(m)	*y*(m)	*z*(m)
1	0.10	0.31	1.12
2	0.09	1.24	1.03
3	0.69	0.36	0.98
4	1.45	0.49	1.05
5	0.61	0.68	1.46
6	1.12	1.27	1.41

Table 2. The calculation results of the spatial position of the second group of simulated small warhead fragment

NO.	*x*(m)	*y*(m)	*z*(m)
1	0.55	0.18	1.29
2	0.88	0.48	1.31
3	1.04	0.63	1.26
4	1.47	0.71	1.45
5	1.43	1.06	1.38

Through simulation experiments, the warhead fragment spatial position acquisition and reconstruction modeling based on light field imaging can obtain the real three-dimensional position of warhead fragments, which verifies that the theoretical model and calculation method are feasible. Since this experiment uses a low-velocity simulated small warhead fragments, it does not require high sampling rate of the light field camera, and the calculation amount is relatively low. From the imaging quality point of view, the spatial characteristics of each warhead fragment can be seen intuitively. For smart ammunition, the warhead fragments formed by its explosion are in high-velocity motion state, so the resolution and sampling rate of the light field camera need to be improved. The method of the light field camera with micro lens array can obtain the warhead fragment spatial position, and provide an important theoretical and practical basis for further research on the spatial position calculation and reconstruction modeling of high-velocity warhead fragments. In addition, in the actual shooting range, the impact of the shock wave and firelight formed by the smart ammunition explosion is also an issue that needs to be considered in practice. In short, through the micro lens array imaging mechanism and reconstruction method in this paper, it provides a scientific methodology for the next step of the multiple light field camera intersection test.

5. Conclusions

In this paper, the imaging mechanism of the light field camera is analyzed; according to the relation of the main lens plane, the micro lens array plane and the image sensor plane of the light field camera, combining the propagation direction of the warhead fragments in the light field camera, the total radiation energy received by the image sensor is given; and the reconstruction modeling of the warhead fragments is derived based on the light field imaging and the calculation function of the warhead fragments on the refocused image plane. By using the four-dimensional information of the light field camera, combine the coordinate positions of the lens plane and the coordinate positions of the image sensor plane, the analytical model of the warhead fragment spatial position is established. Through the simulation experiment, the imaging images of multiple warhead fragments are collected, and the spatial position of the warhead fragments is calculated according to the calculation and reconstruction modeling of the warhead fragment imaging position of the micro lens array. For the test system of warhead fragment spatial position acquired by dual light field camera intersection, the theoretical method and model proposed in this paper can solve the problem that warhead fragments cannot be distinguished and reconstructed due to overlapping or occlusion in space. It lays a foundation for further establishing a more complete theoretical model of warhead fragment spatial position based on the light field imaging mechanism.

Acknowledgement

This work has been supported by Project of the Key Programs of Shaanxi Science and Technology Department (No.2020GY-125), National Natural Science Foundation of China (No.62073256), and Xi'an Science and Technology Innovation talent service enterprise project (No.2020KJRC0041).

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