Three-Dimensional Coordinate Positioning of Aerial Blast Point

Wang Zemin, Jia Tiandan

School of Electronic Information Engineering, Xi'an Technological University, Xi'an 710021, China

Abstract

Aiming at the problem that the positioning accuracy of passive acoustic localization algorithm is influenced by wind speed, temperature, humidity and other factors, a passive optical positioning algorithm is proposed. Time delay of a plane cross array technology is easy to introduce blind spot area, a five element solid array positioning model based on time delay is proposed. In this paper, the geometric relations and parameters of the array elements of the three-dimensional array of five elements are studied; using the knowledge of spatial geometry and the cosine theorem, the calculating formula of target location is derived; according to the error theory, the error analysis is carried out. The experimental results show that, the passive optical positioning technology used in this paper is feasible, and the algorithm can overcome the influence of passive acoustic localization accuracy is affected by environmental temperature, humidity, wind speed, noise, to meet the certain measuring condition can ensure better measurement precision.

Key words: TIME DELAY OF ARRAY, PASSIVE OPTICAL POSITIONING, THE THREE-DIMENTIONAL ARRAY OF FIVE ELEMENTS, ERROR ANALYSIS

1. Introduction

Some weapon system according to its attack target and damage mechanism often need in aerial fixed-point detonated and detonate the position coordinates directly determines the damage its effectiveness, and aerial blast point coordinates of the test become an important index to measure the performance of a weapon, so the burst point 3D coordinate measurement is for the weapon range test is one of the important objectives [1,2]. The present test method of 3D coordinate has some problems, such as: double array CCD test system, visualization of the system is good, but the capture rate is low; acoustic target, the object to be measured from the acoustic signal as the signal source, however sound signal test accuracy is easily affected by environmental temperature, humidity, wind direction, wind and other factors; The measurement method of photoelectric detection target with high speed camera combination, the test of photoelectric detection target is accurate, but by the high speed photography coverage of the field of view and image resolution is limited, there is the problem of small field of view[3,4,5,6]. In order to improve the above problems, the passive optical positioning technology based on the array is proposed. The technology uses a plurality of photoelectric detectors to build the base array, and receive the intrinsic characteristics of the object itself, which is an explosive light signal. Through a certain signal processing circuit to obtain an effective signal, and then obtain the time delay of the optical signal received between the two detectors by the precise timing circuit[7,8,9,10]. According to the coordinate calculation formula of mathematical modeling, the 3D coordinate information of the final point is obtained.

Compared with the previous model of plane positioning, this paper uses the three-dimensional array of five elements positioning model to carry on the whole three-dimensional space, and the positioning range is improved. Compared with the previous multiple elements cross localization model, this paper used the five elements localization model to overcome the cross array model cannot accurately locate the point of the distance that are equal to the elements of the model, which can overcome the failure of the blind spot area[11,12].Compared with the passive acoustic localization, the passive optical positioning is used to overcome the influence of noise, wind speed, wind direction, temperature, humidity and so on. The use of passive optical positioning is more rapid response than passive acoustic localization, can realize real-time positioning[13].

2. The aerial blast point coordinate measuring principle

At present, the aerial blast point measurement model of the three-dimensional coordinates commonly used planar array and three-dimensional arrays, among them, the use of the majority is based on matrix model of detection time delay cross array, The cross array detector is arranged symmetrically and the geometrical relation is clear, and the calculation is simple and easy to be simplified, but the most deadly is the cross array can't measure the distance of each detector is equal to the point and the point of the small range around this point. When the explosion point is in the range, the time delay between the signal arrival time delay is zero or almost zero, then the calculation formula based on the principle of time difference is invalid, this gives a very large error and even positioning failure. In order to overcome the impact of this factor, the measurement model of this paper by using the three-dimensional array of five elements, which can solve the problem of measuring blind spots[14,15].

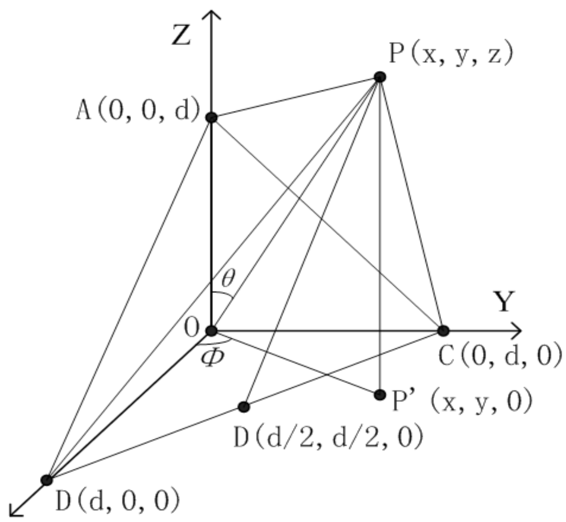

Figure 1. The three-dimensional array of five elements

The three-dimensional array of five elements is shown in figure 1. In $o-xyz$, A, B, C, D and O points are put on the photoelectric detectors, and its coordinates are known by the graph, d is a known constant, P' is the projection point in the xoy plane of the burst point P, φ is a target azimuth angle, θ as target pitch angle. From Figure 1, Firstly, the time difference of the photoelectric detector is obtained by measuring the light source to detectors of different position, and the distance difference between the different position sensors is obtained. Finally, the 3D coordinates of the explosive light can be obtained by using the geometrical knowledge. From the distance formula between two points:

$$PA = \sqrt{(x-d)^2 + y^2 + z^2} \quad (1)$$

$$PB = \sqrt{x^2 + (y-d)^2 + z^2} \quad (2)$$

$$PC = \sqrt{x^2 + y^2 + (z-d)^2} \quad (3)$$

$$PD = \sqrt{\left(x - \frac{d}{2}\right)^2 + \left(y - \frac{d}{2}\right)^2 + z^2} \quad (4)$$

$$PO = \sqrt{x^2 + y^2 + z^2} \quad (5)$$

$PO = r$, $PA = r_1$, $PB = r_2$, $PC = r_3$, $PD = r_4$,

knowledge of the three-dimensional space:

$$x = r\sin\theta\cos\varphi \quad (6)$$

$$y = r\sin\theta\sin\varphi \quad (7)$$

$$z = r\cos\theta \quad (8)$$

The time difference between the point light source P to A point and O point is t1, the time difference between O and B is t2, the time difference between O and C is t3, the time difference between O and D is t4:

$$r_1 - r = ct_1 = u \quad (9)$$

$$r_2 - r = ct_2 = v \quad (10)$$

$$r_3 - r = ct_3 = w \quad (11)$$

$$r_4 - r = ct_4 = q \quad (12)$$

From formula (1),(5),(9):

$$-2dx + d^2 = u^2 + 2ur \quad (13)$$

$$-2dy + d^2 = v^2 + 2vr \quad (14)$$

$$-2dz + d^2 = w^2 + 2wr \quad (15)$$

$$-dx - dy + \frac{d^2}{2} = q^2 + 2qr \quad (16)$$

By (13), (14), (15) the expression of the three-dimensional coordinates of the point can be got:

$$x = \frac{u^2 + 2ur - d^2}{-2d} = \frac{c^2t_1^2 - d^2 + 2ct_1r}{-2d} \quad (17)$$

$$y = \frac{v^2 + 2vr - d^2}{-2d} = \frac{c^2t_2^2 - d^2 + 2ct_2r}{-2d} \quad (18)$$

$$z = \frac{w^2 + 2wr - d^2}{-2d} = \frac{c^2t_3^2 - d^2 + 2ct_3r}{-2d} \quad (19)$$

Will (6), (7), (8) respectively by (13), (14), (15), (16) available:

$$-2dr\sin\theta\cos\varphi + d^2 = u^2 + 2ur \quad (20)$$

$$-2dr\sin\theta\sin\varphi + d^2 = v^2 + 2vr \quad (21)$$

$$-2dr\cos\theta + d^2 = w^2 + 2wr \quad (22)$$

$$-2dr\sin\theta(\cos\varphi + \sin\varphi) + d^2 = 2q^2 + 4qr \quad (23)$$

From formula (20),(21),(23):

$$r = \frac{2q^2 + d^2 - u^2 - v^2}{2u + 2v - 4q} \quad (24)$$

From formula (20),(21)the expression of tangent azimuth can be got:

$$\tan\varphi = \frac{v^2 + 2vr - d^2}{u^2 + 2ur - d^2} = \frac{c^2 t_2^{\,2} - d^2 + 2ct_2 r}{c^2 t_1^{\,2} - d^2 + 2ct_1 r} \quad (25)$$

From (8), (24) a pitch angle cosine expression:

$$\cos\theta = \frac{w^2 + 2wr - d^2}{-2dr} \quad (26)$$

This formula can be the burst point distance measurement for distance from origin:

$$r = \frac{2q^2 + d^2 - u^2 - v^2}{2u + 2v - 4q} = \frac{c^2\left(2t_4^{\,2} - t_1^{\,2} - t_2^{\,2}\right) + d^2}{2c(t_1 + t_2 - 2t_4)} \quad (27)$$

According to the cosine theorem, the geometrical relationship of Figure 1 is available:

$$c^2 t_1^{\,2} + 2rct_1 - d^2 + 2dr\sin\theta\cos\varphi = 0 \quad (28)$$

$$c^2 t_2^{\,2} + 2rct_2 - d^2 + 2dr\sin\theta\sin\varphi = 0 \quad (29)$$

$$c^2 t_3^{\,2} + 2rct_3 - d^2 + 2dr\cos\theta = 0 \quad (30)$$

$$c^2 t_4^{\,2} + 2rct_4 - \frac{1}{2}d^2 + dr\sin\theta\cos\varphi + dr\sin\theta\sin\varphi = 0 \quad (31)$$

From the upper formula:

$$-d^2 = c^2\left(2t_4^{\,2} - t_1^{\,2} - t_2^{\,2}\right) + 2rc(2t_4 - t_1 - t_2) \quad (32)$$

(25) can be used:

$$\tan\varphi = \frac{2t_4(ct_4 + 2r) - t_1(ct_1 + 2r)}{2t_4(ct_4 + 2r) - t_2(ct_2 + 2r)} \quad (33)$$

Given that the blast site is located in the far field, : r>> ct_i:

$$\tan\varphi \approx \frac{2t_4 - t_1}{2t_4 - t_2} \quad (34)$$

$$\varphi \approx \tan^{-1}\left(\frac{2t_4 - t_1}{2t_4 - t_2}\right) \quad (35)$$

From formula (27), (30):

$$\cos\theta = \frac{c^2\left(2t_4^{\,2} - t_1^{\,2} - t_2^{\,2} + t_3^{\,2}\right) + 2rc(2t_4 - t_1 - t_2 + t_3)}{-2dr} \quad (36)$$

Given that the blast site is located in the far field, r>> ct_i :

$$\cos\theta \approx \frac{c(t_1 + t_2 - t_3 - 2t_4)}{d} \quad (37)$$

$$\theta \approx \cos^{-1}\left(\frac{c(t_1 + t_2 - t_3 - 2t_4)}{d}\right) \quad (38)$$

All above, three-dimensional coordinate information of blast point can be obtained.

3. Error analysis

The positioning performance of the target is related to the speed of light C, the geometrical dimension d of the array of photoelectric detector, and the error of time delay estimation. In theory, the array size under certain conditions, the accuracy of time delay estimation is the key to the performance of the target location. In practical applications, the speed of light C and the size of d can be corrected and calibrated in advance. The influence of delay estimation error on location accuracy is considered. The standard deviation for the assumption of time delay estimation is: $\sigma_\tau = \sigma_{\tau_1} = \sigma_{\tau_2} = \sigma_{\tau_3} = \sigma_{\tau_4}$, the propagation velocity C of light in the air is about 3.0×10^8 m/s. According to the error theory, the function $y = f(x_1, x_2, \cdots, x_n)$ is set up, and the standard deviation of the error is:

$$m_y = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 \cdot m_1^{\,2} + \left(\frac{\partial f}{\partial x_2}\right)^2 \cdot m_2^{\,2} + \cdots + \left(\frac{\partial f}{\partial x_n}\right)^2 \cdot m_n^{\,2}} \quad (39)$$

Where $x_1, x_2, \cdots, x_n$ for direct observation of the unknown quantity, y is unknown variable to be calculated, $m_1, m_2, \cdots, m_n$ for the unknown error standard deviation.

3.1. Azimuth error analysis

According to the error theory, the standard deviation of the azimuth error is from the formula (39):

$$\sigma_\varphi = \sigma_\tau\sqrt{\left(\frac{\partial\varphi}{\partial t_1}\right)^2 + \left(\frac{\partial\varphi}{\partial t_2}\right)^2 + \left(\frac{\partial\varphi}{\partial t_3}\right)^2 + \left(\frac{\partial\varphi}{\partial t_4}\right)^2} \quad (40)$$

By (40) the accuracy of azimuth estimation is:

$$\sigma_\varphi \approx \sigma_\tau \frac{\sqrt{(2t_4 - t_2)^2 + (2t_4 - t_1)^2 + 4(t_1 - t_2)^2}}{(2t_4 - t_2)^2 + (2t_4 - t_1)^2}$$

$$= \frac{\sigma_\tau}{1 + \tan^2\varphi}\sqrt{\frac{(2t_4 - t_2)^2 + (2t_4 - t_1)^2 + 4(t_1 - t_2)^2}{(2t_4 - t_2)^4}}$$

$$= \frac{c\sigma_\tau}{dr\sin^2\theta}\sqrt{5 + 5\tan^2\varphi - 8\tan\varphi} \quad (41)$$

By the formula (41), the error estimation accuracy of the azimuth angle is related to the pitch angle, azimuth angle, time delay estimation error and array size of the photoelectric detector.

3.2. Pitch angle error analysis

According to the error theory, the standard deviation of the azimuth error is from the formula (39):

$$\sigma_\theta = \sigma_\tau\sqrt{\left(\frac{\partial\theta}{\partial t_1}\right)^2 + \left(\frac{\partial\theta}{\partial t_2}\right)^2 + \left(\frac{\partial\theta}{\partial t_3}\right)^2 + \left(\frac{\partial\theta}{\partial t_4}\right)^2} \quad (42)$$

By (42) the accuracy of the pitch angle estimation can be estimated:

$$\sigma_\theta = \frac{\sqrt{7}c}{d\sin\theta}\sigma_\tau \quad (43)$$

By the formula (43), the estimation accuracy of pitch angle error is related to the pitch angle, time delay estimation error and array size of photoelectric detector.

3.3. Distance error analysis

According to the error theory, the standard deviation of the azimuth error is from the formula (39):

$$\sigma_r = \sigma_\tau \sqrt{\left(\frac{\partial r}{\partial t_1}\right)^2 + \left(\frac{\partial r}{\partial t_2}\right)^2 + \left(\frac{\partial r}{\partial t_3}\right)^2 + \left(\frac{\partial r}{\partial t_4}\right)^2} \quad (44)$$

By (44) the accuracy of the distance estimation is:

$$\sigma_r = \sigma_\tau \sqrt{\frac{(ct_1 + r)^2 + (ct_2 + r)^2 + 4(ct_4 + r)^2}{(t_1 + t_2 - 2t_4)^2}} \quad (45)$$

Given that the blast site is located in the far field, r>> ct_i, from formula (32), (45):

$$\sigma_r \approx \frac{2rc}{d^2}\sqrt{6r^2 + 4d^2 - 6dr\sin\theta(\cos\varphi + \sin\varphi)}\sigma_\tau \quad (46)$$

By the (46), the distance error estimates are related to the array size, the time delay estimation accuracy, the pitch angle, the azimuth angle, and the explosion light to the measurement model.

4. Error simulation and analysis

In the practical application environment, the measurements of external environment is more complex, in addition effective speed of light error affected by temperature, humidity, wind speed caused by the outside, and array optical model, size and signal arrived time of different position of photoelectric detector difference. In order to verify the performance of the five element array model, the MATLAB simulation can be used to view and compare the effect of the different variables on the positioning results.

4.1. Simulation analysis of azimuth error

Formula (41) shows that: In the case of certain error of time delay estimation, the accuracy of the error estimation of the three-dimensional array of five elements is related to the pitch angle, azimuth angle and array size of the explosive light. Assume $\sigma_\tau = 1ns$, $c = 3.0\times10^8 m/s$, $r = 1000m$, the relationship between the azimuth error and the array element size and the pitch angle is shown in figure 2, figure 3, figure 4:

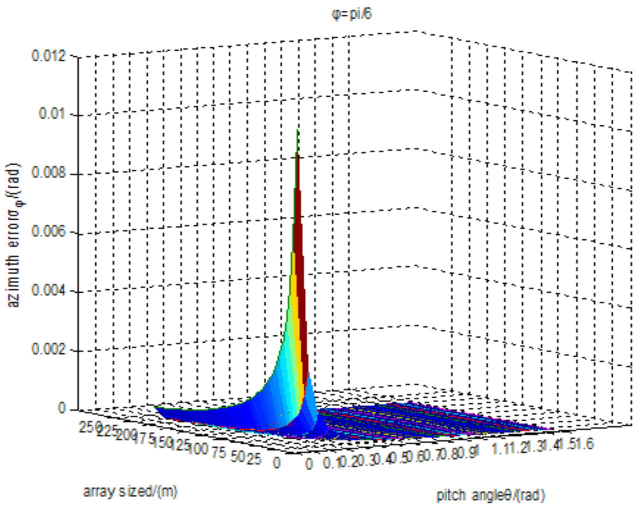

Figure 2. φ = 30° error of azimuth and pitch angle and array size variation diagram

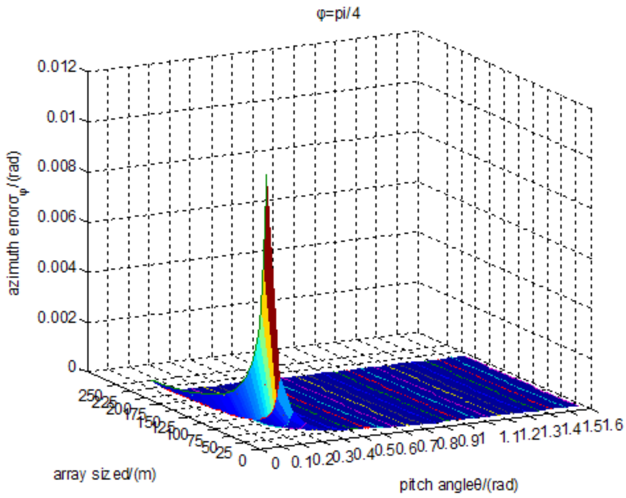

Figure 3. φ = 45°error of azimuth and pitch angle and array size variation diagram

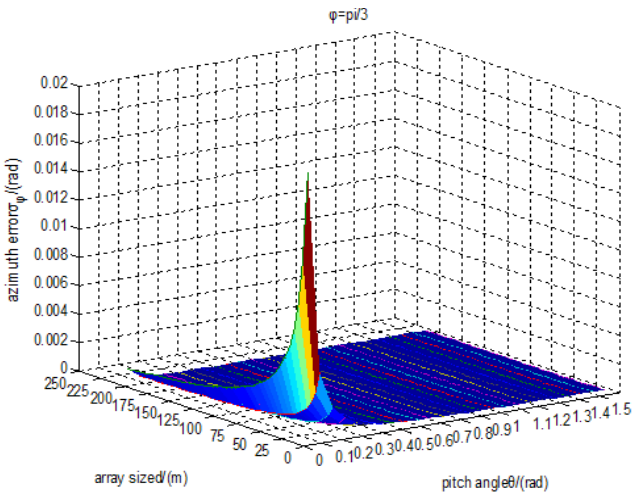

Figure 4. φ = 60° error of azimuth and pitch angle and array size variation diagram

From Figure 2 we can see that when the array size d or pitch angle θ close to 0, the azimuth error are suddenly increased; When the d >75 *m* or θ > 0.3 *rad* error in the distance slowly decreases and tends to a constant value, can obtain small azimuth error. From Figure 3 and Figure 4 shows the azimuth angle has little effect on the azimuth error when the size change when d >75 *m* or θ > 0.3 *rad*; When the array size d or pitch angle θ close to 0, the rate of change of the azimuth error is large and suddenly increases more quickly.

4.2. Pitch angle error simulation analysis

Formula (43) shows that: In the case of certain error of time delay estimation, the pitch angle error estimation accuracy of the five element array is inversely proportional to the size of the array, size of the explosive light and the pitch angle of the optical detector, has nothing to do with the explosion light azimuth angle. Assume $\sigma_\tau = 1ns, c = 3.0\times10^8 m/s$, the relationship of the pitch angle error with the array element size and the pitch angle is shown in figure 5:

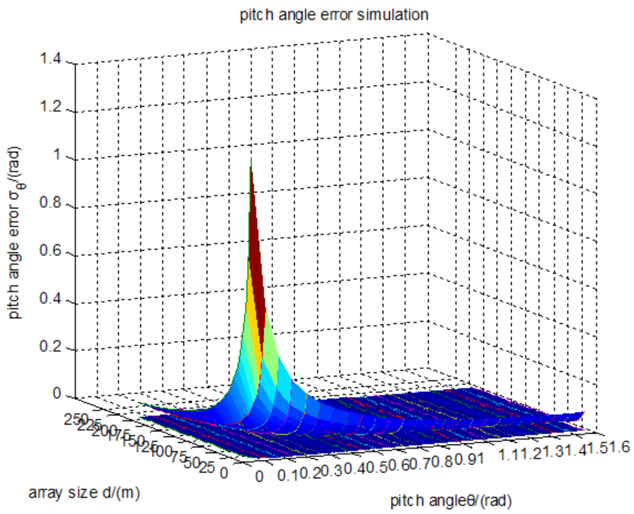

Figure 5. Relationship chart of pitch angle error and pitch angle and array element size

As can be seen from Figure 5, array size d < 75 *m* or θ < 0.6 *rad* ,pitch angle error increases rapidly; d >75 *m* or θ > 0.6 *rad*, , azimuth error changes gradually sharp decreases and tends to be gentle, indicating that the range can be obtained within a smaller range of angle error.

4.3. Distance error simulation analysis

Formula (46) shows that: In the case of certain error of time delay estimation, the accuracy of the distance error estimation of the five element array is related to the pitch angle, the azimuth angle and the array size of the explosive light. Assume $\sigma_\tau = 1ns$, $c = 3.0\times10^8 m/s$, $r = 1000m$, the relationship between the azimuth error and the array element size and the pitch angle is shown in figure 6, figure 7, figure 8, figure 9:

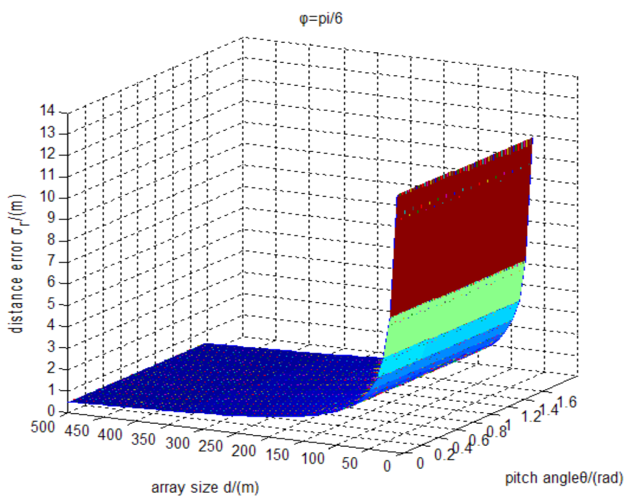

Figure 6. φ=30°Relationship chart of distance error and pitch angle and array element size

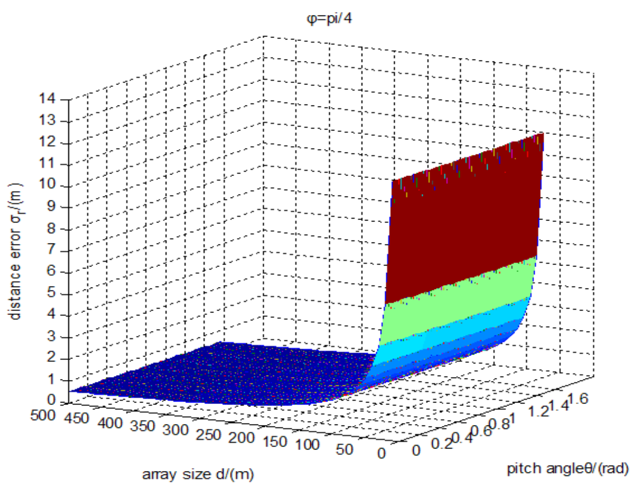

Figure 7. φ=45° Relationship chart of distance error and pitch angle and array element size

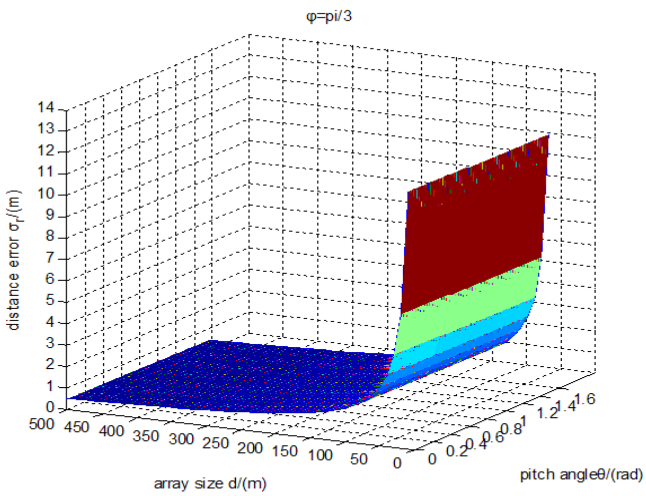

Figure 8. φ=60° Relationship chart of distance error and pitch angle and array element size

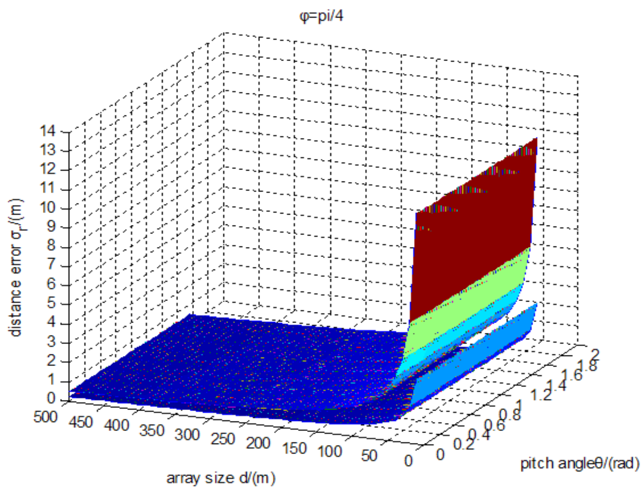

Figure 9. $r = 1000m$, $r = 500m$ distance error and pitch angle and array element size change diagram

From Figure 6: Under the condition of $r = 1000m$,φ=30° , when $d > 150m$, the distance error is close to 1 m , when the array size is constant, the greater the pitch angle the smaller the distance error. Contrast Figure 6, figure 8, Figure 7 shows, the change of azimuth angle has little effect on the distance error. Observe figure 9, explosive light distance of the five element array model of the origin of the r=1000m is located at the top of the r=500m chart. Under the condition of $r = 1000m$, when the array size is $d > 180m$, the distance error $\sigma_r < 1m$. Under the condition of $r = 500m$, when the array size is d > 40 m, the distance error $\sigma_r < 1m$. By (2-8) and Figure 9, when the target distance of five element array model is far from the origin, the higher the dimension of the model is, the accuracy of distance error estimation can be reduced by increasing the array element size.

In the analysis, the three-dimensional array of five elements can effectively use the passive light to 3D coordinate location of the explosion point. Time delay estimation error σ_τ in a certain precision range, by setting a reasonable array element size d can ensure the positioning accuracy, more precise 3D coordinates.

5. Testing and data analysis

In order to facilitate the experimental data measurement and verification of the accuracy of the positioning performance, do a certain point of tipping, and get the tipping point P (150,80,420). $\sigma_\tau = 1ns$, the experiments were done in $d = 100m$ and $d = 200m$ respectively, experimental data are as follows:

Table 1. Experimental data comparison

Array element size	$d = 100m$	$d = 200m$
Theoretical value	$r = 453.1004303683677m$	$r = 453.1004303683677m$
	$\theta = 67.963773059854550^\circ$	$\theta = 67.963773059854550^\circ$
	$\varphi = 28.07248693585296^\circ$	$\varphi = 28.07248693585296^\circ$
Theoretical delay	$t_1 = -7.5451884559166693 \times 10^{-8} s$	$t_1 = -7.5451884559166693 \times 10^{-8} s$
	$t_2 = -2.2233815524578 \times 10^{-8} s$	$t_2 = 2.94566393950626 \times 10^{-8} s$
	$t_3 = -3.024900390949964 \times 10^{-7} s$	$t_3 = -5.835721829307027 \times 10^{-7} s$
	$t_4 = -6.7729100669065667 \times 10^{-8} s$	$t_4 = -9.887374391188373 \times 10^{-8} s$
Model results	$r = 453.1004303683644m$	$r = 452.1539093026779m$
	$\theta = 78.22525783796219^\circ$	$\theta = 71.6292738379157^\circ$
	$\varphi = 27.92255949610703^\circ$	$\varphi = 36.00560266779345^\circ$
Theoretical delay	$\sigma_r = 2.55055058058256m$	$\sigma_r = 5.54072770790071m$
	$\sigma_\theta = 0.002432359240007^\circ$	$\sigma_\theta = 0.00418174032675^\circ$
	$\sigma_\varphi = 0.000001016445715^\circ$	$\sigma_\varphi = 0.000006728933896^\circ$

6. Conclusions

In this paper, a passive optical positioning algorithm based on the three-dimensional array of five elements is studied, which solves the problem of 3D coordinates of the point of the air blast in the near surface, the error factors affecting the positioning accuracy of the positioning algorithm are analyzed theoretically, the corresponding error analysis chart is given, after the comprehensive analysis, the improvement method and the way are put forward. Finally, the correctness of the error analysis is verified by experiments. Experimental results show: the size of the array element directly determines the size of the measurement error, when the measured burst point distance origin measurement is certain, the greater array element spacing, the higher measuring accuracy. In this paper, the passive optical positioning algorithm and the three-dimensional array of five elements model are well realize the 3D coordinate positioning of aerial blast point, avoid the planar cross array bring in blind area, overcome the problem that the passive acoustic localization is easily influenced by environmental factors.

Acknowledgements

This work was supported by key science and technology program of Shaanxi province of China (Grant No. 2015GY018).

References

1. Antonio Teixeira, Ricardo Ferreira, Jacklyn D. Reis, et al. (2014) Ultra-High-Capacity Passive Optical Network Systems with Free-Space Optical Communications. *Fiber and Integrated Optics*, 33(3), p.p.149-162.
2. Gregory J.E, Garbin H.D, Mark D.L. (2000) Comparison of Methods for 3D Target Localization from Seismic and Acoustic Signatures. *SPIE*, p.p.154-164.
3. Roger Y. TSAI (1987) A Versatile Camera Calibration Technique for High-accuracy 3D Machine Vision Metrology using off-the-shelf TV Cameras and Lenses. *IEEE Journal of Robotics and Automation*, 3(4), p.p.323-334.
4. Yunl F.U, Liu Lin, Wu Ke-yong (2005) Application of Linear CCD for Position Measurement. *Proc of SPIE*, 6024, p.p. 614-618.
5. Ruiy, Florencio D. (2004) Time Delay Estimation in the Presence of Correlated Noise and Reverberation. *IEEE International Conference on Acoustics, Speech, and Signal Processing*, p.p.133-136.
6. Benesty J, Chen J.D, Huang Y.T. (2004) Time Delay Estimation via Linear Interpolation and Cross Correlation. *IEEE Trans Speech and Audio Processing*, 12(5), p.p.509-519.
7. Piersol A.G. (1981) Time Delay Estimation using Phase Data. *IEEE Transactions on Acoustics, Speech and Signal Processing*, 29(3), p.p.471-477.
8. Knapp C.H, Cater G.C. (1976) The Generalized Correlation Method for Estimation of Time Delay. *IEEE Transactions on Acoustics, Speech and Signal Processing*, 24(4), p.p.320-327.
9. Yiteng Huang (2001) *Real-time Acoustic Source Localization with Passive Micro-phone Array*. Ph.D thesis,
10. Raja Jurdark, Cristina Videira Lopes, Pierre Baldi (2004) An Acoustic Identification Scheme for Location Systems. *Proc. of The IEEE/ACS International Conference on Pervasive Services*, p.p.61-70
11. Saeid Pashazadeh, Mohsen Sharifi (2009) A Geometric Modelling Approach to Determining the Best Sensing Coverage for 3-Dimensional Acoustic Target Tracking in Wireless Sensor Networks. *Sensors*, 9(9), 6764-6794.
12. Lu S.T, Chou C, Wu Y.P. (1994) Newton-Raphson Method for Accuracy Enhancement of Electro-optical Targeting System. *IEEE Proc-Sci,Meas,Technology*, 141(3), p.p.160-164.
13. Janos Sallai, Will Hedgecock, Peter Volgyesi, et al. (2011) Weapon Classification and Shooter Localization using Distributed Multichannel Acoustic Sensor. *Journal of Systems Architecture*, 57(10), p.p. 869-885.
14. Thyagaraju Damarla, Lance M.Kaplan, Gene T. Whipps (2010) Sniper Localization Using Acoustic Asynchronous Sensors. *IEEE Sensors Journal*, 10(9), p.p.1569-1478
15. Toni Makinen, Pasi Pertila (2010) Shooter Localization and Bullet Trajectory, Caliber, and Speed Estimation Based on Detected Firing Sounds. *Applied Acoustics*, 71(10), p.p.902-913