RESEARCH ON DETECTION SYSTEM OF LARGE DISTANCE MULTI-AXES BORESIGHT

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To satisfy the detection requirement of multi-axes boresight for weapon system, a novel detection method of large distance multi-axes boresight based on inertial reference is promoted and a detection system is designed. A two-dimensional galvanometer is used in the detection system to aim the direction of measured axis. Gyroscope and photoelectric encoder are adopted to measure the vector coordinates of each measured axis in inertial space. The spatial angle between measured axes can be calculated by their vector coordinates and then the boresight of measured axes can be detected by their spatial angle. The mathematical model of multi-axes boresight detection is built and error factors of detection system are analyzed and calculated. Experimental analytical results show that the actual measurement error is 13.8″ which meets the requirements of multi-axes boresight detection in wild completely.

Keywords: *multi-axes boresight; large distance; detection system; inertial reference.*

OCIS code: alignment, detection.

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ИССЛЕДОВАНИЕ СИСТЕМЫ ОПРЕДЕЛЕНИЯ ПАРАЛЛЕЛЬНОСТИ СИЛЬНО РАЗНЕСЁННЫХ В ПРОСТРАНСТВЕ ОСЕЙ МНОГООСЕВЫХ ПРИЦЕЛЬНЫХ СИСТЕМ

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Чтобы удовлетворить требованиям, предъявляемым к измерению сосности каналов в многолучевых системах военного назначения, был разработан и проверен экспериментально новый метод измерения, пригодный для контроля многолучевых систем с сильно разнесёнными осями, основанный на точных измерениях их положения в инерциальном пространстве. В измерительной системе используется двумерный гальванометр для определения направления каждой данной оси. Гироскоп и фотоэлектрический датчик используются для измерения векторных координат каждой из осей в инерциальном пространстве. Пространственный угол между осями может быть вычислен по их векторным координатам, и тогда направления осей могут быть определены по их пространственным углам. Была разработана математическая модель измерителя соосности, проанализированы и вычислены погрешности измерений. Экспериментальные исследования показали, что фактическая погрешность измерения составляет 13.8″ и удовлетворяет требованиям, предъявляемым к системам измерения параллельности осей в многолучевых системах военного назначения.

1. Introduction

Multi-axes boresight is one of the most important indexes for modern multi-axes weapon system and it is the guarantee for the weapon system to hit targets. Multi-axes boresight needs to be detected not only in the process of system design and assembling but also in use process periodically, because the optical-mechanical system may be disordered due to environmental factors [1, 2]. However, with the rapid development of weapon system the detection of its multi-axes boresight is more and more difficult. The difficulty reflects in the following two aspects specifically: firstly, the number and species of measured axes are increasing; secondly, the distance between measured axes is getting larger. For example, some weapon systems have both optical axes and non-optical axes and the distance between these measured axes is more than several meters.

There are several traditional methods to detect multi-axes boresight, such as by employing projection target board, pentaprism, laser optical axis instrument, large aperture collimator and so on [3–7]. The projection target board method has the advantage of convenience and low cost, but its accuracy is susceptible to the environment. For the pentaprism method the rotation of characteristic direction will lead to a large optical axis error, thus the detecting accuracy will be influenced. Laser optical axis instrument method has self-calibration capability, which can eliminate the interference from human factor, but the method causes great difficulty in system assembling and it has highly special application. Large aperture collimator has a high accuracy, but its volume is very big and inconvenient to carry. Israel CI Company presents a new video detection system for multi-axes boresight of weapon system named AWBS (Advanced Weapon Boresight System) [8]. It extracts cooperation target image by a CCD installed on the weapon barrel and superposes the image on optical sensors, thereby the error between the sighting axis and shooting axis can be calculated. This method makes non-optical axes visualization and has a great advantage in large distance detection, but it is susceptible to the environment when extracting cooperation target image. Gyroscope is adopted in the multi-axes boresight detection by Ralph R. Jones [9]. This method is flexible, but it is difficult to mount the gyroscope on various types of measured axis accurately.

The key for large distance multi-axes boresight is establishing a high precision measurement reference and measuring the relationship between measurement reference and other measured object accurately [10]. In this case, a novel detection method of large distance multi-axes boresight based on inertial reference is proposed in this paper. The inertial coordinate system is used as the measurement reference and the measured axes are regarded as free vectors in inertial coordinate system. The spatial angle between the measured axes can be calculated by the vector coordinates of each measured axis. Then the multi-axes boresight can be detected by the spatial angle. This paper is structured as follows. Section 1 introduces the researching background. Detection principle is described in section 2. Section 3 demonstrates the mathematical model of the proposed method. In section 4 a prototype is built based on the proposed method and is applied to a practical measurement. The performance of the proposed method is validated. Section 5 draws a natural conclusion.

2. Detection principle and detection system

The multi-axes boresight detection for weapon system usually detects the boresight between sighting axes and shooting axes. The principle of large distance multi-axis boresight detection proposed in this paper can be expressed as follows. Assume that there is no angular motion for the measured object in the detection process. Coordinate system is established in inertial space to serve as a measuring reference. The sighting axes and shooting axes are seen as several unit vectors in inertial coordinate system. The coordinate values of these vectors can be measured by detection system. Then the spatial angle between sighting axes and shooting axes can be calculated by their coordinate values and the boresight of sighting axes and shooting axes can be detected by their spatial angle.

Generally, there are three different types of axes need to be detected for weapon system, the non-optical axes like the aiming line of fire control radar or gun barrel, the optical axes of active optical sensors like laser rangefinder or laser pointer and the optical axis of passive optical sensors like IR/visible imaging device. Non-optical axis can be measured by fitting a mirror adapter and measuring the optical axis of the mirror by autocollimation. Detection of the optical axis of passive optical sensors can be measured by projecting a reference reticle beam directly into passive optical sensors and using the passive optical sensors to report the direction of optical axis. The optical axis of active optical sensors can be measured by directly imaging the reference reticle projected from the active optical sensors to the CCD of detection system and the position of laser spot can report the direction of optical axis.

The working principle and composition of detection system is shown in fig. 1. The detection system is comprised of an integrated multi-spectral target, collimator, imaging assembly, two-dimensional galvanometer and triaxial gyroscope. The integrated multi spectral target includes mulitspectral integrated source and IR/visible general reticle board. The integrated multi spectral target can eliminate the error of optical axis between infrared sensor and visible sensor.

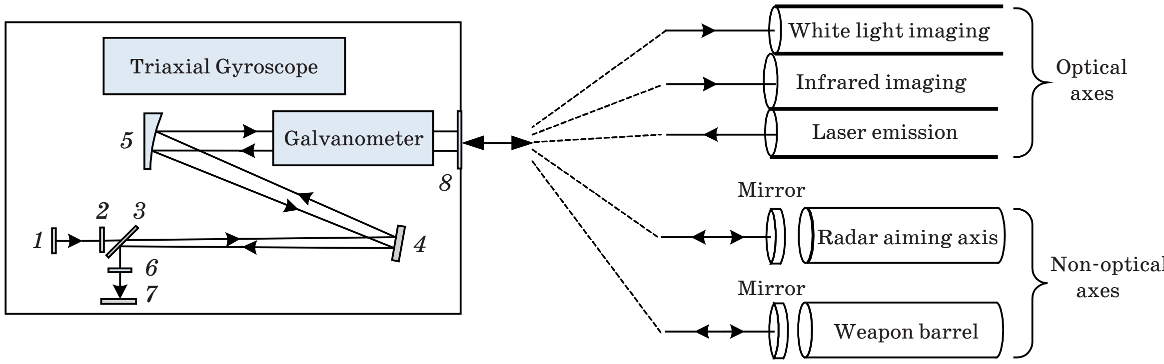

Fig. 1. Detection system working principle diagram. *1* – multitspectral integrated source, *2* – reticle, *3* – spectroscope, *4* – secondary mirror, *5* – primary mirror, *6* – up-conversion board, *7* – CCD, *8* – window.

Reflecting collimator system is adopted in the detection system, so its volume can be reduced greatly by folding light path. Imaging assembly includes CCD videocamera and up-conversion board. The up-conversion board can covert the 1.06/1.54 μm infrared laser to visible laser, so that the CCD videocamera can capture their images. The galvanometer is rotating until the reticle center coincides with the collimated image center so that the measured axis is parallel to the optical axis of detection system. The triaxial gyroscope is connected with detection system case and thus the measurement is practiced by mathematical model in an indirect way.

All detections begin with a reference axis acquisition and the weapon barrel is set as reference axis generally. A technician positions the detection system in the vicinity of the weapon barrel and commands the galvanometer to conduct a spiral search pattern. It causes a collimated light beam from the detection system to spiral until the beam reflected from the mirror before the weapon barrel is captured. Once a reticle from the CCD videocamera of detection system is identified during the spiral scan, the orientation offset is calculated from the offset of the reflected reticle to a center pixel of the CCD videocamera and the orientation offset can be eliminated by the galvanometer. At this point the gun barrel parallels to the optical axis of detection system and the reference axis acquisition is complete. Then the technician positions the detection system in the vicinity of the other measured axis respectively and makes the optical axis of detection system parallel to the measured axis by the same way as above (For passive optical sensor the IR/visible reticle image that projected from the detection system is centered in the measured sensor; for the active optical sensor the laser spot that from the measured sensor is centered in the CCD videocamera of detection system; for non-optical weapon/sensor the reticle image reflected from the mirror is centered in the CCD videocamera of detection system). When the optical axis of detection system is aligned with these measured axes respectively, the spatial angle between the measured axes can be calculated by their vector coordinates and then the multi-axes boresight can be detected by the spatial angle.

3. Mathematical modeling

3.1. Relevant coordinate systems

Since the mathematical model of spatial angle measurement involves only coordinate rotation transformation and the rotation angle of coordinate system is not relevant to its origin position, the origin position may be ignored when defining the coordinate system. In order to simplify the calculation all coordinate systems are set with the same origin.

3.1.1. Inertial coordinate system

Inertial coordinate system is a reference frame of the total measurement. In order to simplify the calculation the x-axis is defined as the reference axis. The z-axis is defined as pointing to the bottom of the reference axis. The y-axis completes the right-handed orthogonal coordinate system.

3.1.2. Detection system coordinate system

The detection system coordinate system is a coordinate system which stands for detection system. The x-axis is defined as in the forward direction of the detection system. The z-axis is defined as pointing to the bottom of detection system. And the y-axis completes the right-handed orthogonal coordinate system.

3.1.3. Optical axis coordinate system

The optical axis coordinate system is a coordinate system which stands for the optical axis of detection system. The x-axis is defined as the optical axis. The z-axis is defined as pointing to the bottom of optical axis. The y-axis completes the right-handed orthogonal coordinate system. The initial optical axis coordinate system coincides with the measuring unit coordinate system if the direction of optical axis is not adjusted.

3.2. Measurement model derivation

As shown in fig. 2 the transformation from the detection system coordinate system to the optical axis coordinate system has to go through two rotations by z-axis and y-axis.

The matrix representation of the coordinate system rotation transformation is

$$C_m^o = \begin{bmatrix} \cos\lambda_p & 0 & \sin\lambda_p \\ 0 & 1 & 0 \\ -\sin\lambda_p & 0 & \cos\lambda_p \end{bmatrix} \times \begin{bmatrix} \cos\lambda_a & \sin\lambda_a & 0 \\ -\sin\lambda_a & \cos\lambda_a & 0 \\ 0 & 0 & 1 \end{bmatrix} = \qquad (1)$$

$$= \begin{bmatrix} \cos\lambda_p\cos\lambda_a & \cos\lambda_p\sin\lambda_a & \sin\lambda_p \\ -\sin\lambda_a & \cos\lambda_a & 0 \\ -\sin\lambda_p\cos\lambda_a & -\sin\lambda_p\sin\lambda_a & \cos\lambda_p \end{bmatrix},$$

where λ_a and λ_p are the azimuth and pitch of optical axis measured by photoelectric encoders. Because of the coordinate rotation transformation matrix is an orthogonal matrix, the matrix representation rotation from the optical axis coordinate system to the detection system coordinate system is

$$C_o^m = (C_m^o)^{-1} = (C_m^o)^{\mathrm{T}}. \qquad (2)$$

As shown in fig. 3 the transformation from the inertial coordinate system to the detection system coordinate system has to go through three rotations by z-axis, y-axis and x-axis.

The matrix representation of the coordinate system rotation transformation is

$$C_i^m = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} =$$

$$= \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ -\sin\psi\cos\phi + \cos\psi\sin\theta\sin\phi & \cos\psi\cos\phi + \sin\psi\sin\theta\sin\phi & \cos\theta\sin\phi \\ \sin\psi\sin\phi + \cos\psi\sin\theta\cos\phi & -\cos\psi\sin\phi + \sin\psi\sin\theta\cos\phi & \cos\theta\cos\phi \end{bmatrix}, \qquad (3)$$

where Ψ, θ and ϕ are attitude of the detection system measured by gyroscope. According to eq. (3), the matrix representation rotation from the detection system coordinate system to the inertial coordinate system is

$$C_m^i = (C_i^m)^{\mathrm{T}}. \qquad (4)$$

According to eq. (3) and eq. (4), the matrix representation rotation from the optical axis coordinate system to the inertial coordinate system is

$$C_o^i = C_m^i C_o^m. \qquad (5)$$

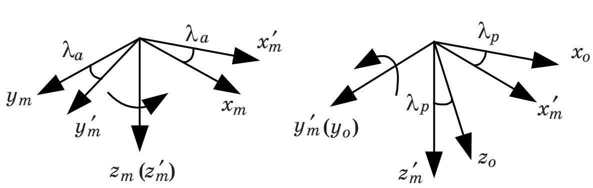

Fig. 2. Detection system coordinate system rotating diagram.

When the detection system captures the direction of measured axis successfully, the measured axis is parallel to the optical axis of the detection system. Therefore the unit vector of

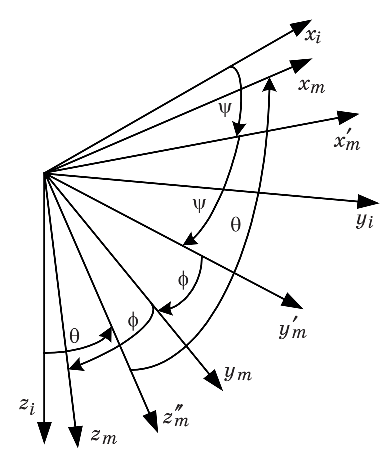

Fig. 3. Inertial coordinate system rotating diagram.

the measured axis in the optical axis coordinate system is

$$\mathbf{r}_m^o = [1 \quad 0 \quad 0]^{\mathrm{T}}, \tag{6}$$

So, the unit vector of measured axis in the inertial coordinate system is

$$\mathbf{r}_m^i = C_o^i \mathbf{r}_m^o. \tag{7}$$

According to the definition of inertial coordinate system, the unit vector of reference axis in the inertial coordinate system is

$$\mathbf{r}_r^i = [1 \quad 0 \quad 0]^{\mathrm{T}}. \tag{8}$$

The spatial angle between reference axis and measured axis can be calculated by Eq. (9)

$$\theta = \arccos(\mathbf{r}_r^i, \mathbf{r}_m^i), \ \theta \in [0°, 180°]. \tag{9}$$

4. Experiment and Analysis

4.1. Prototype assembly a nd accuracy analysis

In order to test the practical effect of the detection method proposed in the paper, a prototype of detection system is designed and assembled on a small optical platform whose size is 600×300 mm, as is shown in fig. 4.

Factors affecting the accuracy of detection prototype include aiming error, gyroscopes measurement errors and encoder measurement errors.

4.1.1. Aiming error

Aiming at the measured object accurately is a precondition for boresight detection and the aiming accuracy is related to the resolution of optical system in prototype. The actual measurement result of the prototype's focal length is $f = 516.81$ mm, the center distance of two pixels is approximately d = 10.6 μm. Therefore the aiming error of the optical system is

$$\sigma_o = \frac{d}{f} = 4.2''. \tag{10}$$

The aiming accuracy of the prototype is pixel level, so the aiming error of prototype is also u_1 = 4.2″ for non-optical weapon/sensor or active optical sensor. For passive optical sensor the aiming error is related to the measured sensor, since the image in the passive optical sensor is used to report the direction of its optical axis.

4.1.2. Gyroscope measurement error

The prototype adopts three single-axis fiber optic gyroscopes which are R&D in Russia Fizoptika Company and their model is VG910H. The nominal bias instability of the fiber optic gyroscope is 5 deg/h. These three single-axis fiber optic gyroscopes are installed orthogonally and their quadrature error can be neglected after calibrated. The time of the multi-axes boresight detection by the promoted method is within 20 min, in this case, the cumulative error of fiber optic gyroscopes in measuring the attitude of detection system is $\sigma_g \le 8.9''$. Using mathematical model of the multi-axes boresight detection established above, the error of multi-axes boresight detection which is caused by gyroscope measurement error is u_2 = 10.3″.

4.1.3. Encoder measurement error

The nominal accuracy of the photoelectric encoder in galvanometer is σ_g = 8μrad ≈ 1.7″. Similarly, calculated by mathematical model of the multi-axes boresight detection established above, the error of multi-axes boresight detection which is caused by photoelectric encoder measurement error is u_3 = 3.9″.

In summary, the total error of the prototype can be calculated by

$$u = \sqrt{u_1^2 + u_2^2 + u_3^2} = 11.8''. \tag{11}$$

4.2. Measurement experiment

In the experiment a two-sided plane mirror is set as the measured object which is marked in fig. 4 and the spatial angle of the two-sided plane mirror's optical axes is measured to be 16°32′41″

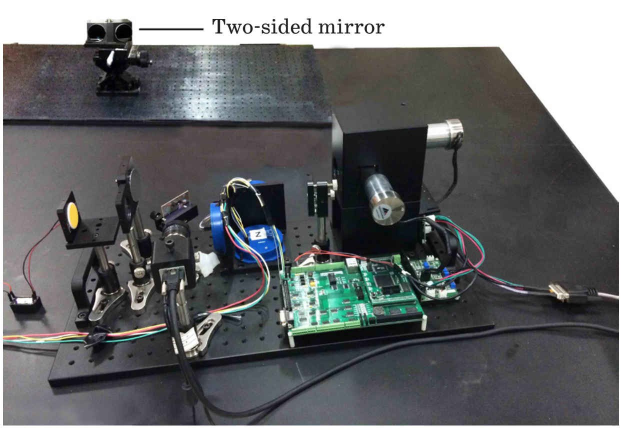

Fig. 4. Experimental prototype.

Measurement data sheet

No.	Measured axis unit vector			Angle	Value difference
	x	y	z		
1	0.95859	0.28262	0.03495	16°32′43″	13.1″
2	0.95862	0.28252	0.03496	16°32′23″	6.9″
3	0.95862	0.28256	0.03486	16°32′29″	0.9″
4	0.95863	0.28251	0.03483	16°32′17″	12.9″
5	0.95859	0.28264	0.03493	16°32′46″	16.1″
6	0.95861	0.28257	0.03484	16°32′28″	1.9″
7	0.95859	0.28265	0.03486	16°32′46″	16.1″
8	0.95861	0.28258	0.03500	16°32′35″	5.1″
9	0.95861	0.28257	0.03488	16°32′30″	0.1″
10	0.95857	0.28271	0.03492	16°32′02″	27.9″

by an autocollimation theodolite whose accuracy is 0.5″.

The optical axis of left plane mirror is set as a reference axis and the optical axis of right plane mirror is set as a measured axis in the experiment. Firstly the prototype is aligned with the reference axis to determine the inertial coordinate system. Secondly the prototype is aligned with the measured axis to measure the coordinate value of measured axis unit vector and the coordinate value of reference axis unit vector is known. Lastly the spatial angle between the reference axis and the measured axis can be calculated by their coordinate values. In order to simulate a large distance measurement the technician holding the detection system moves a certain distance (approximately 10 m) freely before aiming the measured axis. The measurement is repeated ten times and the results are shown in table.

After multiple sets of measurements the measuring error of spatial angle measurement can be calculated by eq. (12). The results reveal that the error analysis is identical with the experimental results and completely meeting the requirements of multi-axes boresight detection in wild with detection error is 0.1 mrad (approximately 20″).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} = 13.8'' < 20''(n = 10). \qquad (12)$$

5. Conclusions

For the challenge of “variety and large distance” in the multi-axes boresight detection for modern weapon system a novel method for the detection of large distance multi-axes boresight based on inertial reference is proposed in this paper. The mathematical model for the detection of multi-axes boresight is built and the error factors of the detection system are analyzed and calculated. Experimental analytical results show that the actual measurement error is 13.8″, which satisfies the requirement of detection. Setting inertial space as a common measurement reference enables the measurement reference to transfer in detection of multi-axes boresight effectively and makes the detection process more flexible and efficient while ensuring detection accuracy.

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