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A new transfer alignment of airborne weapons based on relative navigation

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ABSTRACT

The traditional transfer alignment for airborne weapons are inadequate to fulfill practical requirement, because of the complicated and unknown wing flexure deformation. To solve this problem, a new transfer alignment method based on relative navigation is proposed. The alignment process is achieved by computing the real-time relative motion between the different inertial units. Besides, the kalman filter is performed to estimate and correct the alignment errors. By this way, it can not only skip the complex model of flexure angle, but also improve the alignment performance. Theoretical analyses and simulation results show that the proposed method can accomplish the transfer alignment in the wing flexure situations, and the relative attitude accuracy can reach the arc second level after about 100 s. Compared with the traditional transfer alignment, the new method is practical and has high-precision.

1. Introduction

Nowadays, airborne weapons have become the main attack ways of a fighter, because of the high accuracy and validity. For inertial-guided weapons, their performance largely depends on the precision of the slave inertial measurement units (SIMU). However, limited by the cost and installation space, the SIMU does not usually satisfy the actual requirements. Compared with the master inertial measurement units (MIMU), the SIMU precision is always lower one or two orders in magnitude [1]. Therefore, the SIMU does not have the ability of initial alignment by itself.

Transfer alignment is a widely used alignment method before the SIMU goes into working. In this process, the outputs of MIMU are used as the references to SIMU, to make the physical or mathematical platform to coincide with the navigation frame [2,3]. Without transfer alignment, the weapon system cannot complete its attack missions. Due to the apparent military value, transfer alignment has become the mainstream of initial alignment in airborne weapons, shipboard weapons, tactical missiles, etc.

Generally, the researches on transfer alignment are mostly devoted into the alignment model, alignment time and maneuver requirement, etc. Depending on the different matching parameters, transfer alignment contains the measurement parameters matching method (e.g., acceleration and angular velocity) and the calculation parameters matching method (e.g., attitude, velocity, and position). Until the "velocity plus attitude" matching was proposed by Kain and Clouiter in 1989, transfer alignment entered into a fast development and universal application period [4]. Based on Refs. [5–7], the alignment results of experiments on the Apache helicopter and F-16 fighter showed the attitude accuracy have reached to 1 min of arc, under the "velocity plus attitude" matching method and Wing-Rock maneuver. The similar researches in Refs. [8,9] indicated the transfer alignment can also be applied in the ship's strapdown inertial attitude reference system. Besides, the $H\infty$ kalman filter in Refs. [10–12] was employed to design the transfer alignment of near-space supersonic vehicle. The turntable tests illustrated that $H\infty$ filter promoted stochastic stability to resolve the uncertainty problems from wing flexure and vibration.

However, regardless of the type of transfer alignment, the fundamental theories are essentially analogous. Through subtracting or multiplying the parameters between MIMU and SIMU as measurement information, the attitude errors or position errors are computed in a standard or modified kalman filter[13–15]. Because the calculations in MIMU and SIMU are independent, the measurement information has lower relevance to the error equations of SIMU. Additionally, the two-order Markov process, used as the model of flexure angle in traditional transfer alignment, cannot match the practical environment. These defections will result in an intricate calculation process and unsatisfactory alignment accuracy. To address these issues, a new transfer alignment based on the relative navigation is proposed in this paper. Unlike previous, the final transfer alignment is accomplished by computing the interrelationship between MIMU and SIMU, according to the relative navigation algorithm. As a part of the relative attitude, it does not need the extra flexure angle model. Therefore, the new transfer alignment has a strong practical value in application and need to explore in the future.

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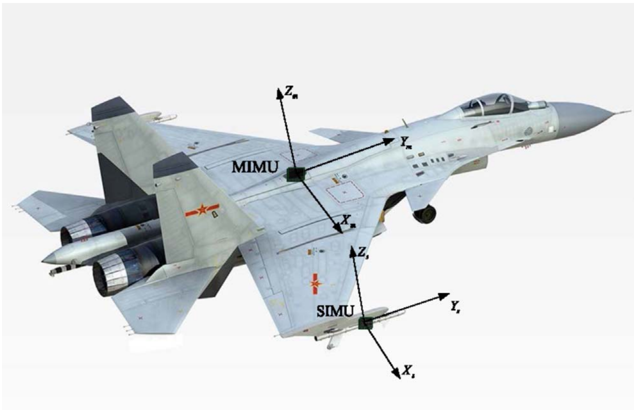

Fig. 1. Sensors location.

The remainder of this paper is organized as follows. Section 2 presents the principle of relative navigation. In Section 3, the relative navigation errors are estimated in the kalman filter. Section 4 is the observability analyses. The simulation results and key discussions are presented in Section 5. Section 6 is the conclusion.

2. Principle of relative navigation

2.1. Sensors location

As shown in Fig. 1, the MIMU and SIMU are located in the fighter and airborne weapon, respectively. Usually, there is only one MIMU per fighter and one SIMU per weapon.

The MIMU and SIMU abide the Right-Front-Up coordinates. The X-axis and Y-axis direct to the right and front of the fighter, respectively. The Z-axis is perpendicular to the XOY plane. The subscripts m and s are the indicator of respective coordinates.

2.2. Relative navigation algorithm

2.2.1. Relative attitude

In practical installation process, the SIMU coordinates do not always coincide with the MIMU coordinates. As shown in Fig. 2, the SIMU coordinates can be obtained through three rotations from MIMU coordinates [16].

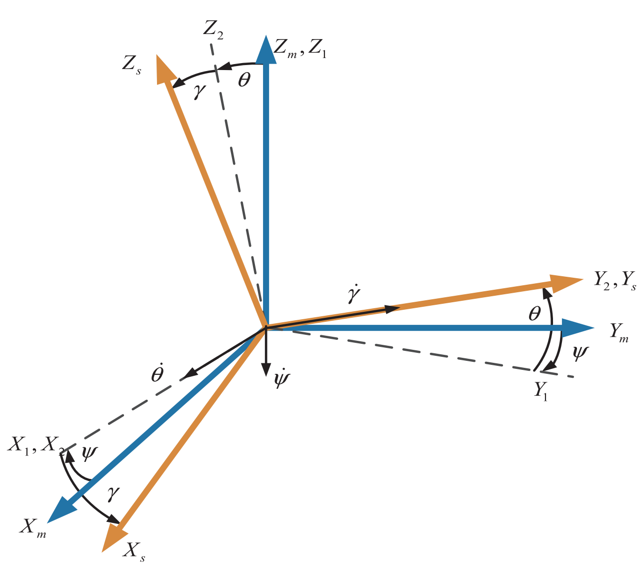

Fig. 2. Relative attitude.

$$(x_m, y_m, z_m) \xrightarrow[Z]{\text{Rotation}(-\Psi)} (x_1, y_1, z_1) \xrightarrow[X]{\text{Rotation}(\theta)} (x_2, y_2, z_2) \xrightarrow[Y]{\text{Rotation}(\gamma)} (x_s, y_s, z_s) \tag{1}$$

The relative attitude matrix $\boldsymbol{C}_m^s$ from MIMU coordinates to SIMU coordinates can be obtained as:

$$\boldsymbol{C}_m^s = \begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ \sin\gamma & 0 & \cos\gamma \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} \cos\gamma\cos\psi + \sin\gamma\sin\theta\sin\psi & -\cos\gamma\sin\psi + \sin\gamma\sin\theta\cos\psi & -\sin\psi\cos\theta \\ \cos\theta\sin\psi & \cos\theta\cos\psi & \sin\theta \\ \sin\gamma\cos\psi - \cos\gamma\sin\theta\sin\psi & -\sin\gamma\sin\psi - \cos\gamma\sin\theta\cos\psi & \cos\gamma\cos\theta \end{bmatrix} \tag{2}$$

where ψ, θ, and γ are the heading angle, pitching angle and rolling angle of SIMU coordinates relative to MIMU coordinates, respectively. Because $\boldsymbol{C}_m^s$ is an orthogonally matrix, the relative attitude matrix $\boldsymbol{C}_s^m$ from SIMU coordinate to MIMU coordinate is the transposed matrix of $\boldsymbol{C}_m^s$.

$$\boldsymbol{C}_s^m = [\boldsymbol{C}_m^s]^T \tag{3}$$

$$\boldsymbol{C}_s^t = \boldsymbol{C}_m^t \boldsymbol{C}_s^m \tag{4}$$

Generally, the MIMU attitude matrix $\boldsymbol{C}_m^t$ is exactly known. The SIMU attitude matrix $\boldsymbol{C}_s^t$ can be obtained by computing the relative attitude matrix $\boldsymbol{C}_s^m$. However, when the wing flexure occurs, $\boldsymbol{C}_s^m$ becomes a time-varying function. Its differential equation can be defined as:

$$\dot{\boldsymbol{C}}_s^m = \boldsymbol{C}_s^m \{\boldsymbol{\omega}_{ms}^s \times\} \tag{5}$$

where {} is the anti-symmetric matrix consisted by the bracketed vector.

Marking $\boldsymbol{\omega}_{is}^s$ and $\boldsymbol{\omega}_{im}^m$ are the outputs of the gyros in SIMU and MIMU, can be calculated as:

$$\{\boldsymbol{\omega}_{ms}^s \times\} = \{\boldsymbol{\omega}_{is}^s \times\} - \boldsymbol{C}_m^s \{\boldsymbol{\omega}_{im}^m \times\} \boldsymbol{C}_s^m \tag{6}$$

Associating Eqs. (5) and (6), the differential equation of relative attitude matrix $\boldsymbol{C}_s^m$ is obtained as:

$$\dot{\boldsymbol{C}}_s^m = \boldsymbol{C}_s^m \{\boldsymbol{\omega}_{is}^s \times\} - \{\boldsymbol{\omega}_{im}^m \times\} \boldsymbol{C}_s^m \tag{7}$$

The Eq. (7) contains 9 first-order differential equations, which can be calculated through the method of numerical integration. For the computing convenience and high precision, the fourth-order Runge-Kutta algorithm is selected in this paper.

2.2.2. Mechanical calibration equations

Fig. 3 shows the relative position between the MIMU and SIMU. $\boldsymbol{R}_m$ and $\boldsymbol{R}_s$ are the position vectors of MIMU and SIMU in the inertial coordinates, respectively. $\boldsymbol{R}$ is the relative position vector of SIMU in the MIMU coordinates. According to the geometric relationship, the position equation can be obtained as:

$$\boldsymbol{R}_s = \boldsymbol{R}_m + \boldsymbol{R} \tag{8}$$

Differentiating the both sides of Eq. (8) in the inertial coordinates, the velocity equation can be obtained as:

$$\left.\frac{d\boldsymbol{R}_s}{dt}\right|_i = \left.\frac{d\boldsymbol{R}_m}{dt}\right|_i + \left.\frac{d\boldsymbol{R}}{dt}\right|_i \tag{9}$$

According to the Coriolis Theorem, the second item in Eq. (9) can be changed as:

$$\left.\frac{d\boldsymbol{R}}{dt}\right|_i = \left.\frac{d\boldsymbol{R}}{dt}\right|_m + \boldsymbol{\omega}_{im} \times \boldsymbol{R} \tag{10}$$

Associating the Eqs. (9) and (10), the velocity equation is modified as:

$$\left.\frac{d\boldsymbol{R}_s}{dt}\right|_i = \left.\frac{d\boldsymbol{R}_m}{dt}\right|_i + \left.\frac{d\boldsymbol{R}}{dt}\right|_m + \boldsymbol{\omega}_{im} \times \boldsymbol{R} \tag{11}$$