Research on improved fine alignment methods

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Abstract. Based on the hypothesis of small values of misalignment angles, compass alignment and linear Kalman alignment are common fine alignment methods. The algorithm of compass alignment has good robustness, but the convergence efficiency and accuracy of alignment are contradictory, which is necessary to set appropriate control parameters to reconcile. Because Kalman alignment method is based on a deterministic filtering model, the algorithm is relatively stable, but the drift of IMU (Inertial Measurement Unit) will cause the drift of the errors of misalignment angles. In order to take into account the effects of both long and short damping periods on compass alignment, the exponential finite time-varying damping period is used to improve the convergence efficiency of azimuth alignment. In order to solve the divergence of horizontal misalignment angles of Kalman precise alignment algorithm, a real-time correction algorithm of attitude matrix with full feedback of misalignment angle estimations is introduced. The simulation and turntable experiments verify the effectiveness of the improved methods.

1. Introduction

Damping period is the key factor affecting the accuracy of alignment and convergence efficiency of compass alignment. There are many factors to be considered when setting the parameter of damping period, which are mainly focusing on the environmental interference characteristics, the noise characteristics of gyroscope and accelerometer [1-2]. The more factors considered be, the better the accuracy and efficiency of compass alignment theoretically will be, but if the errors of all factors cannot be accurately modeled, the optimum damping period cannot be guaranteed. From the above analysis, how to find a simple and effective method to control the parameter of damping period is the inevitable requirement of the reliability of compass alignment. Neural network and Particle Swarm Optimization (PSO) algorithms are used to obtain the damping period of compass alignment, and the damping periods obtained are constant. Therefore, the contradiction between convergence efficiency and the accuracy of compass alignment cannot be fundamentally solved. The shorter the damping period of compass alignment be, the faster the convergence of alignment and the larger the corresponding convergence error will be. On the contrary, when the damping period is longer, the alignment results are exactly opposite to that of the short period. Therefore, combining the advantages of long damping period and short damping period, the convergence efficiency and accuracy can be better considered. The model of Kalman fine alignment is generally based on the assumption of small misalignment angles and ignores the high-order error terms. Since the misalignment angles estimated are not used for the correction of platform errors as the compass alignment, and the errors of alignment will drift because of the cumulative effect of IMU bias errors. In order to solve the problem of drift of alignment errors, IMU biases are estimated online as a state variable and compensated in alignment [7-8]. However, there is a risk of alignment failure when the bias estimation error is large or divergent.

In this paper, the principle of compass alignment method is analyzed firstly. In order to take into account the influence of long and short damping periods on compass alignment, the exponential finite time-varying damping period is introduced to improve the convergence efficiency of azimuth alignment on the basis of guaranteeing the convergence accuracy. Aiming at the divergence of horizontal misalignment angles of linear Kalman fine alignment algorithm, a real-time attitude matrix correction algorithm based on the full feedback of misalignment angle estimations is introduced, which can improve the accuracy of fine alignment. The simulation and turntable experiments verify the effectiveness of the improved methods.

2. Improved compass alignment and Kalman alignment

2.1. Exponential finite time-varying compass alignment

The basis of compass alignment is the principle of compass effect, which adjusts the misalignment angles of the platform through the northward velocity error of GINS (Gimbaled Inertial Navigation System). The principle of compass alignment of GINS is shown in Figure 1 below.

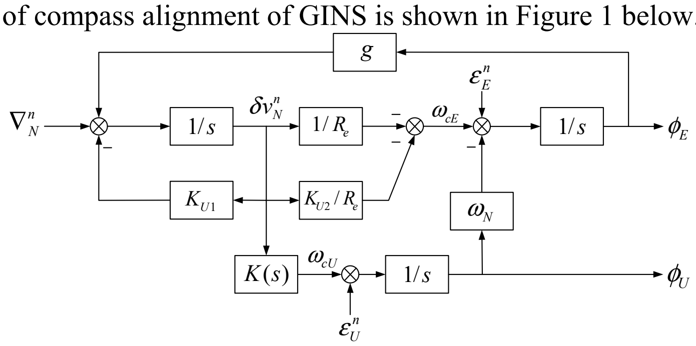


Fig.1 Principle diagram of azimuth fine alignment of GINS

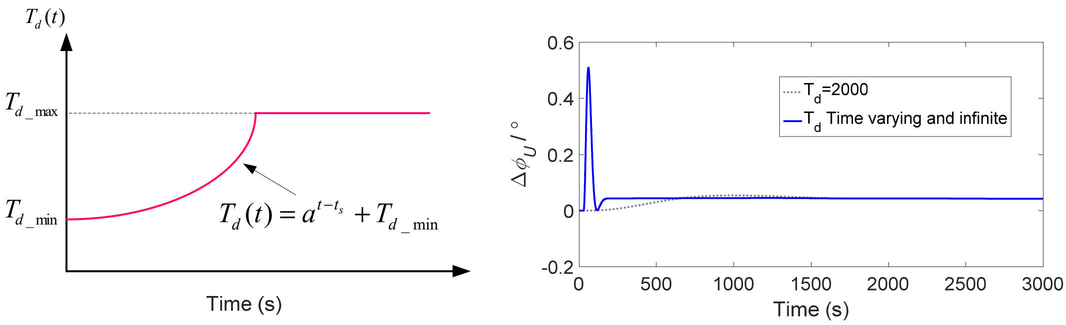
Where ∇_E^n and ∇_N^n are equivalent bias of eastward and northward accelerometers respectively, ε_E^n, ε_N^n and ε_U^n are biases of eastward, northward and vertical gyroscopes respectively, ϕ_E, ϕ_N and ϕ_U are alignment angles of eastward, northward and vertical directions respectively, ω_{cE}, ω_{cN} and ω_{cU} are angular rate applied by the platform respectively, $\omega_N = \omega_{ie}\cos L$, ω_{ie}, g, R_e and L are the angular velocity of the earth rotation, the acceleration of gravity, the radius of the earth and the latitude of the platform respectively, $K_{E1} = K_{N1} = 3\sigma$, $K_{E2} = K_{N2} = \dfrac{\sigma^2(1/\xi^2+2)}{\omega_s^2} - 1$, $K_{E3} = K_{N3} = \dfrac{\sigma^3}{g\xi^2}$, $K_{U1} = K_{U4} = 2\sigma$, $K_{U2} = \dfrac{4\sigma^2}{\omega_s^2} - 1$, $K_{U3} = \dfrac{4\sigma^4}{g}$, σ is the attenuation coefficient, $T_d = \dfrac{2\pi\xi}{\sigma\sqrt{1-\xi^2}}$, generally there are $\xi = \sqrt{2}/2 \approx 0.707$ and $\omega_s = \sqrt{g/R_e}$ is Schuler frequency. For a typical second-order control system, according to the relationship between σ, ω_d and $\omega_d = 2\pi/T_d$ can be obtained:

$$T_d = \frac{2\pi\xi}{\sigma\sqrt{1-\xi^2}}. \quad (1)$$

Generally speaking, the smaller ω_n or ω_d be, the stronger the anti-jamming ability of the control system and the larger the oscillation period and the slower the convergence will be. If ω_n is set too large, the stability of the system will be improved, but at the same time, the convergence efficiency of compass alignment will be low, especially azimuth alignment. T_d represents the response period of the system. The smaller T_d is, the faster the response and convergence of the system will be. As we known, the larger the oscillation is, the lower the stability of the system will be. Therefore, the relationship between response and stability needs to be balanced in the selection of parameter T_d. In order to make use of the convergence efficiency of small T_d and the stable convergence of large T_d, exponential finite time-varying T_d is introduced to improve the speed and accuracy of azimuth alignment. Assuming that time-varying T_d is expressed as $T_d(t)$, then $T_d(t)$ can be expressed as:

$$T_d(t) = a^{t-t_s} + T_{d0},\ \ T_d(t) \le T_{d\_\max}, \quad (2)$$

where t_s is horizontal alignment time, T_{d0} is the initial value of azimuth alignment time T_d, $T_{d\_\max}$ is the maximum value of T_d. We set $a = 1.01$ in this paper and the change of $T_d(t)$ is shown in Figure 2 (a). Assuming that the misalignment angle is set as $\boldsymbol{\Phi} = [1^\circ, 1^\circ, 1^\circ]$, the azimuth misalignment estimation errors of the improved compass alignment and the traditional compass alignment are shown in Figure 2 (b).



(a) Diagram of finite time-varying $T_d(t)$

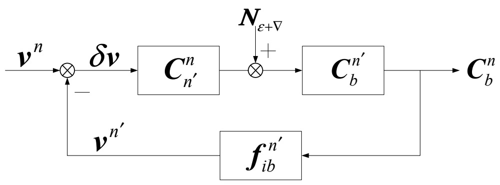
(b) Azimuth alignment errors maps of traditional compass and improved method

Fig.2 Change diagram of $T_d(t)$ and azimuth misalignment angle error

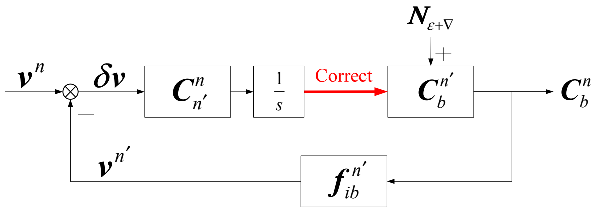
From Figure 2 (b), it can be seen that the azimuth misalignment angle of improved compass alignment enters the convergence state at about $t = 170s$, while the traditional compass alignment enters the convergence state after $t = 1500s$, and the alignment time is reduced by about 8 times.

2.2. Feedback Kalman fine alignment

The errors of horizontal misalignment angle estimation in Kalman fine alignment have drifts, which are caused by the none-compensation of the biases of IMU in the alignment. If the drifts are not suppressed or the alignment process lasts longer, the alignment results will be unavailable. If the biases of IMU are regarded as disturbance inputs, according to the control principle, the steady-state errors caused by the input signals and disturbance signals of the system can be effectively eliminated by concatenating integral element in the forward channel of the control system. Applying the method of eliminating steady-state error in closed-loop control system to traditional Kalman fine alignment algorithm, the signal flowchart of improved Kalman alignment is shown in Fig. 3 (b) and the traditional Kalman alignment is shown in Fig. 3 (a).



(a) Traditional Kalman



(a) Feedback traditional Kalman

Fig.3 Flow chart of traditional Kalman and feedback Kalman fine alignment

Where $\boldsymbol{v}^n$ is the external reference velocity under the navigation system, $\boldsymbol{v}^{n'}$ is the calculated velocity in the computational coordinate system, $\delta\boldsymbol{v}$ is the velocity error, $\boldsymbol{C}_{n'}^{n}$ is the attitude transformation matrix between the navigation system and computational coordinate system, $\boldsymbol{N}_{\varepsilon+\nabla}$ is the bias of IMU. Before joining the integral part, the navigation computer corrects $\boldsymbol{C}_b^{n'}$ and calculates $\delta\boldsymbol{v}$ through IMU data. In the alignment process, the velocity error $\delta\boldsymbol{v}$ is used as the observation quantity, and the value of $\boldsymbol{C}_{n'}^{n}$ is obtained by Kalman filter formula. Therefore, before adding the integral part, $\boldsymbol{C}_b^{n'}$ only provides the calculation process of $\delta\boldsymbol{v}$ to $\boldsymbol{C}_{n'}^{n}$, and there is no direct correction relationship between $\boldsymbol{C}_{n'}^{n}$ and $\boldsymbol{C}_b^{n'}$. Fig. 3 shows that, after the integral link is added, $\boldsymbol{C}_b^{n}$ is not obtained by the multiplication of the estimated value of $\boldsymbol{C}_{n'}^{n}$ and $\boldsymbol{C}_b^{n'}$, but the $\boldsymbol{C}_b^{n'}$ is corrected in each filtering cycle, which realizes the closed-loop integral control between $\boldsymbol{C}_{n'}^{n}$ and $\boldsymbol{C}_b^{n'}$. The direct advantage of the improved algorithm is that the estimated value of $\boldsymbol{C}_{n'}^{n}$ can be directly reflected in $\boldsymbol{C}_b^{n'}$, and $\boldsymbol{C}_b^{n'}$ can accelerate the convergence. The accelerated convergence of $\boldsymbol{C}_b^{n'}$ can lead to the accelerated convergence of misalignment angles. Even if the misalignment angles at the initial time are large, the improved algorithm can make the misalignment angles converge to small values quickly, which cannot only improve the efficiency of alignment, but also reduce or eliminate the cumulative effect of misalignment angle errors through integration part, and thereby eliminate the problem of the drift.

3. Test, Results and Discussions

In order to verify the effects of exponential finite time-varying compass alignment and feedback Kalman fine alignment, a turntable test was used to simulate the stationary base working condition of SINS in laboratory environment. The laboratory turntable is a three-axis turntable, the angular rate control accuracy is $\pm 0.0005^\circ/s$, the angular measurement accuracy is $\pm 0.0001^\circ$, and the IMU is fixed on the plane of the inner frame. The constant drift of FOG (Fiber Optic Gyroscope) is $\varepsilon_C = 0.02(^\circ/h)$ and the angle random walk is $\varepsilon_N = 0.001(^\circ/\sqrt{h})$. The constant bias of accelerometer is $\nabla_C = 100\mu g$, the random walk is $\nabla_N = 10(\mu g/\sqrt{h})$, the sampling period of inertial device is 200Hz, and the experiment time is 900s. The experimental turntable and principle diagram are shown in Fig. 4.

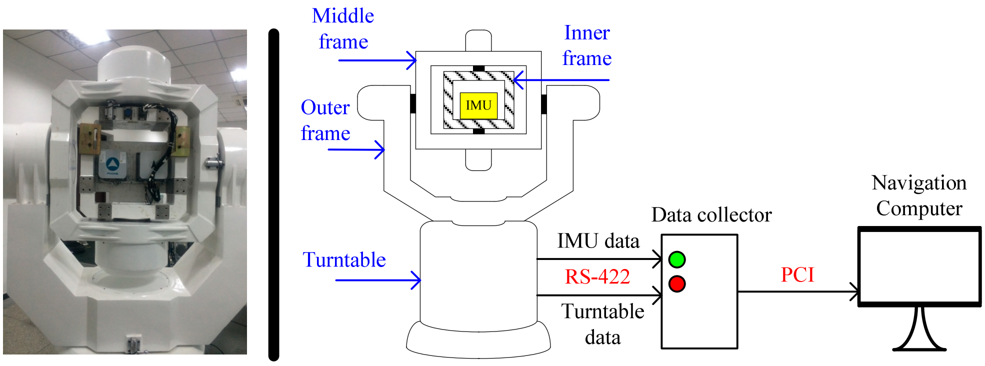


Fig.4 Turntable for experiment and block diagram of experiment principle

In setup of the turntable is shown in Figure 4, RS-422 bus is used between the turntable and the data collector, PCI bus is used between the collector and the navigation computer, and the angle of the output of the turntable is used as the reference. In order to simulate fine alignment, the inner frame's misalignment angle is set as $\alpha = [0^\circ, 0^\circ, 0^\circ]$, so the outputs of the initial alignment algorithm are the errors of misalignment angle estimation. The initial alignment is carried out by traditional compass alignment method, improved compass alignment, Kalman alignment and feedback Kalman alignment respectively. The errors of misalignment angles are in Fig. 5.

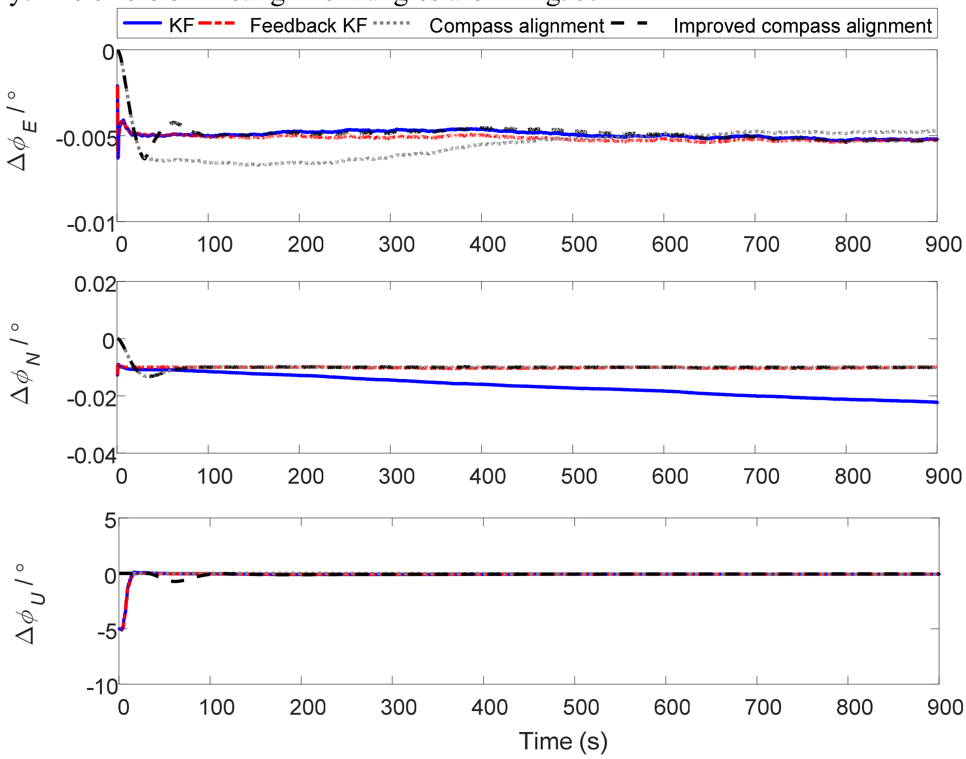


Fig.5 Errors of misalignment angles in turntable experiment

Fig. 5 shows that the eastern misalignment error of traditional compass alignment oscillates at low frequency. The eastern misalignment error of improved compass alignment oscillates at high frequency in the initial stage and converges in about 100 seconds, and there is no oscillation and divergence in the later alignment time. For the north misalignment error, the error of feedback Kalman precision alignment has a higher convergence efficiency than that of compass precision alignment and improved compass alignment, while the error of Kalman alignment has an obvious divergence. For azimuth misalignment angle, the azimuth misalignment error of improved compass oscillates sharply in the initial alignment period, but its error gradually converges around 200 seconds and convergence curve coincides with the Kalman fine alignment and feedback Kalman fine alignment. According to the convergence shown in Fig. 5, assuming that all four algorithms converge from 500 seconds, the misalignment errors of the four algorithms are shown in Table 1.

Tab.1 Misalignment errors of four alignment algorithms in turntable experiments (Unit: º)

algorithms	Eastern error（º）		Northern error（º）		Vertical error（º）	
	Mean	Std	Mean	Std	Mean	Std
Kalman	-0.0051	9.5014e-5	-0.0198	0.0015	-0.0691	4.9923e-4
Feedback Kalman	-0.0053	4.7661e-5	-0.0102	1.4307e-4	-0.0634	4.1065e-4
Compass	**-0.0049**	1.2964e-4	**-0.0100**	5.3425e-5	-0.0642	0.0094
Improved Compass	-0.0051	1.7797e-4	**-0.0100**	5.3535e-5	**-0.0536**	0.0051

From Table 1, we can see that the errors of north and vertical misalignment angles obtained by feedback Kalman alignment are smaller than that of Kalman alignment, and the standard deviation of the three direction misalignment angle errors of feedback Kalman are smaller than that of Kalman alignment. The azimuth misalignment errors of improved compass alignment are significantly smaller than that of traditional compass alignment, and the accuracy is improved by 16.51%.

4. Conclusion

(1) Exponential finite time-varying compass alignment takes into account the advantages of large and small damping periods on the basis of keeping the accuracy unchanged, which greatly improves the alignment efficiency.

(2) Feedback Kalman alignment solves the problem of the drift of horizontal misalignment angles in traditional Kalman alignment by adding integral part.

(3) Feedback Kalman can accelerate the convergence of horizontal misalignment angle by periodically modifying attitude matrix, which provides a technical reference for the initial alignment application with large misalignment angles.

Acknowledgments

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