Research on a filtering method for integrated navigation vibration interference

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Abstract. Low-flying and long-endurance SUAV generally use the piston engine to provide power. The vibration signal in the airframe exhibits a characteristic of multi-vibration-source, wide-band and non-stationary due to lightweight design of SUAV. The vibration will be captured by MIMU, which can significantly affect the accuracy of Kalman filter and even cause the filter fail. Based on the design idea of DOB, this paper proposes a novel filtering method for multi-source vibration interference of integrated navigation system. By designing the disturbance observer, this method successfully estimates and compensates the variable-mean component of the vibration interference of the MEMS device, while the Gauss component can be suppressed by Kalman filter. Experimental results show that the filtering method can accurately estimate and effectively inhibit the multi-source vibration interference caused by the engine. And effectively improves the accuracy and anti-interference capability of the MIMU/GPS system.

1. Introduction

Low altitude and long endurance SUAV generally use the configuration of large aspect ratio and short airframe. In addition, it generally uses composite materials in order to reduce weight. However, its power device (usually using four stroke gasoline piston engine) brings severe vibration interference to the airframe. The structure mode of the SUAV with light and thin features is relatively low, and the vibration is difficult to be effectively attenuated during the process of vibration conduction in airframe. It causes that vibration signal exhibits a complex characteristic of multi-vibration-source, wide-band and non-stationary. When the multi-source vibration captured by MIMU, the signal with the variable-mean, standard-deviation-varying will be input to the Kalman filter, causing the precision decline of the integrated navigation system. Moreover, it may even cause the filter divergence, which may bring great danger to the long endurance SUAV.

Since simple and can effectively improve the robustness of the system, DOBC (Disturbance Observer Based Control) has been widely used in recent years[1-4]. Professor Chen proposed a novel disturbance observer applied to the control of two link robot arm in his publication[5]. In the nonlinear mechanical system, the observer successfully estimates and compensates the unknown interference. If the idea of DOBC is introduced into the design, by establishing the system model, designing the disturbance observer and combining it with the Kalman filter, the anti-interference ability of Kalman filter performance can be improved[6]. In [7,8], to solve problems of stationary base initial alignment, Professor Guo established drift model of navigation sensor, designed disturbance observer, constituted a composite layered anti-interference filter with H_2/H_∞ filter. This method successfully offsets and inhibits the multi-source interference in the system. However, it has never been used in the multi-source vibration system, and never been combined with the Kalman filter.

To solve interference problems in MIMU/GPS integrated navigation system caused by multi-source, wide-band and non-stationary vibration signal in airframe, this paper presents a novel filtering method. In order to verify the effectiveness and superiority of the proposed method, the vibration table test are fulfiled.

2. Vibration Analysis of the Airframe

Low altitude and long endurance SUAV has the characteristics of light and thin, and airframe vibration has the characteristics of multi-source, wide-band and non-stationary. The power spectral density analysis of the airframe vibration signal is shown in Figure 1 with the example of Q-201 UAV. The figure indicates that the main body vibration frequency segment coverage 0-200Hz. The average power spectral density is $0.025g^2$/Hz. Near the central frequency of 15Hz, there is a range of power spectral density up to $0.25g^2$/Hz.

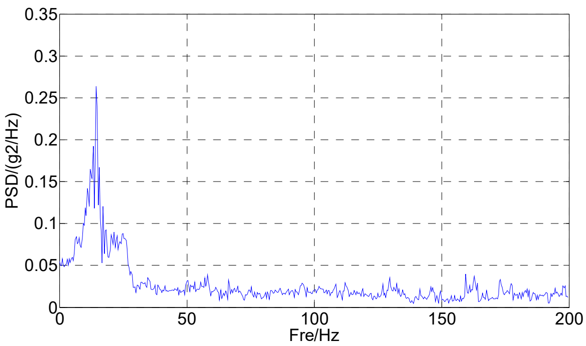


Fig. 1 PSD of the Q-201 vibration signal

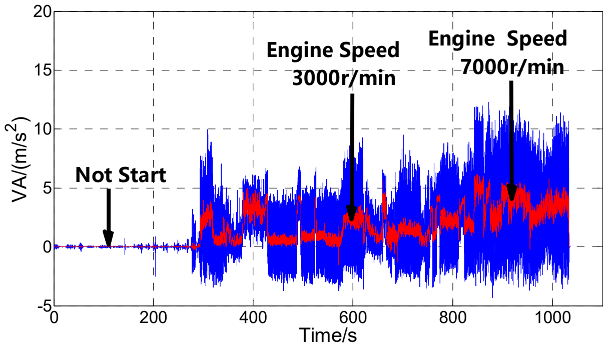


Fig. 2 Q-201 accelerometer vibration signal

The airframe vibration transmits to the MIMU/GPS system, which brings a significant interference to MEMS device. Taking the accelerometer on Z-axis as an example, the output signal of the accelerometer at different speed of the engine is shown in Figure 2. From the diagram, with the change of engine speed, the mean value and amplitude of the disturbance signal of the accelerometer are constantly changing. Disturbance signal peak up to $13m/s^2$, and it presents the time domain characteristics of mean and standard deviation change. After solving the probability density function of the accelerometer signals under different speed conditions, the signal of each condition is presented with the Gauss type distribution.

Results show that the vibration signal of MEMS device is characterized by the variable mean superposed Gauss white noise. The MEMS interference signal is transferred to the integrated navigation system, which makes the precision decline of the Kalman filter and even makes the filter divergence. Conventional Kalman filter is difficult to suppress such interference.

3. Design of the Disturbance Observer

In order to suppress the variable-mean vibration interference, the design idea of DOB is introduced as a reference to estimate and counteract the low frequency and variable mean part of the interference signal. Then, paper combines the disturbance observer with Kalman filter to form a new anti-interference filter of MIMU/GPS integrated navigation system.

In this paper, the interference caused by the vibration signal to the accelerometer is considered. The velocity state model is established in this part, which lays the foundation for the design of the following disturbance observer.

3.1 Establishment of Disturbance Observer Model

The vector $[V_x^n \quad V_y^n \quad V_z^n]^T$ of the SUAV is used as the state variables. Considering the vibration interference, the state model can be expressed as :

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{u} + \boldsymbol{d} \tag{1}$$

Where, $\boldsymbol{A}=2\boldsymbol{\omega}_{ie}^{n}+\boldsymbol{\omega}_{en}^{n}$, $\boldsymbol{\omega}_{ie}^{n}$ is the projection of the earth's rotation angular velocity in the geographic coordinate system; $\boldsymbol{\omega}_{en}^{n}$ is the projection of the rotation angular velocity of the geographic coordinate system relative to geocentric coordinate system in the geographic coordinate system. In the state model (1), $\boldsymbol{u}$ is the system equivalent control, which is expressed as follows:

$$\boldsymbol{u}=\boldsymbol{a}_{ib}^{n}-\boldsymbol{g}^{n} \tag{2}$$

Where, $\boldsymbol{a}_{ib}^{n}$ is the projection of specific force in geographic coordinate system, $\boldsymbol{g}^{n}$ is the gravity acceleration vector in geographic coordinate system.

In the state model (1), $\boldsymbol{d}$ is the vibration disturbance of the body to the navigation system:

$$\boldsymbol{d}=\boldsymbol{d}_{V} \tag{3}$$

Where, $\boldsymbol{d}_{V}$ is velocity interference, expressed as follow:

$$\boldsymbol{d}_{V}=\begin{bmatrix} d_{Vx} & d_{Vy} & d_{Vz} \end{bmatrix}^{T} \tag{4}$$

3.2 Design of the Disturbance Observer

According to the equation (1), the amount of interference $\boldsymbol{d}$ can be written as:

$$\boldsymbol{d}=\dot{\boldsymbol{x}}-\boldsymbol{A}\boldsymbol{x}-\boldsymbol{u} \tag{5}$$

We design the interference estimator $\hat{\boldsymbol{d}}$ to satisfy the equation:

$$\begin{aligned}\dot{\hat{\boldsymbol{d}}} &= \boldsymbol{L}(\boldsymbol{d}-\hat{\boldsymbol{d}}) \\ &= \boldsymbol{L}(\dot{\boldsymbol{x}}-\boldsymbol{A}\boldsymbol{x}-\boldsymbol{u}-\hat{\boldsymbol{d}})\end{aligned} \tag{6}$$

Where, $\boldsymbol{L}$ is the gain matrix of disturbance observer, which influences the estimation performance and stability of the observer.

By defining the intermediate variable

$$\boldsymbol{z}=\hat{\boldsymbol{d}}-\boldsymbol{L}\boldsymbol{x} \tag{7}$$

Then,

$$\hat{\boldsymbol{d}}=\boldsymbol{z}+\boldsymbol{L}\boldsymbol{x} \tag{8}$$

Combined with equation (6), we can obtain

$$\begin{aligned}\dot{\boldsymbol{z}} &= \dot{\hat{\boldsymbol{d}}}-\boldsymbol{L}\dot{\boldsymbol{x}} \\ &= -\boldsymbol{L}\boldsymbol{z}-\boldsymbol{L}(\boldsymbol{A}\boldsymbol{x}+\boldsymbol{u}+\boldsymbol{L}\boldsymbol{x})\end{aligned} \tag{9}$$

In SUAV system, $\boldsymbol{L}$ can be described as follow:

$$\boldsymbol{L}=\mathrm{diag}\{L_1,L_2,L_3\} \tag{10}$$

In summary, disturbance observer for SUAV MIMU/GPS integrated navigation system is designed as follow:

$$\begin{cases}\dot{\boldsymbol{z}}=-\boldsymbol{L}\boldsymbol{z}-\boldsymbol{L}(\boldsymbol{A}\boldsymbol{x}+\boldsymbol{u}+\boldsymbol{L}\boldsymbol{x}) \\ \hat{\boldsymbol{d}}=\boldsymbol{z}+\boldsymbol{L}\boldsymbol{x}\end{cases} \tag{11}$$

According to the disturbance observer (11), it is implied that the estimated value of the vibration disturbance can be obtained by solving the equation of variable differential equation and the calculation formula of the disturbance observer. In addition, in order to ensure the robust stability of the observer, we need to determine the range of gain $\boldsymbol{L}$. By Lyapunov stability theorem, it is proved that, when $L_i>0\,(i=1\sim3)$, the error differential equation of the disturbance observer can keep the global asymptotic stability. To obtain more accurate and faster performance of the observation observer, we need to further regulate the value of $\boldsymbol{L}$ under above constraints.

3.3 Stability of the Disturbance Observer

In the SUAV navigation system, the disturbance observer is used to estimate the low frequency vibration component. This part of the amount of interference changes slowly. So it is reasonable to suppose that

$$\dot{\boldsymbol{d}}=0 \tag{12}$$

The disturbance observer error is defined as follow:

$$\boldsymbol{e}(t) = \boldsymbol{d} - \hat{\boldsymbol{d}} \tag{13}$$

Combined with equation (6)(10), we can obtain

$$\dot{\boldsymbol{e}} = \dot{\boldsymbol{d}} - \dot{\hat{\boldsymbol{d}}} = \boldsymbol{L}(\hat{\boldsymbol{d}} - \boldsymbol{d}) \tag{14}$$

That is, the observer error is governed by

$$\dot{\boldsymbol{e}} = -\boldsymbol{L}\boldsymbol{e} \tag{15}$$

Theorem: For the MIMU/GPS integrated navigation system (1), when the gain $\boldsymbol{L}$ in the observer (11) is chosen as

$$\boldsymbol{L} = \mathrm{diag}\{L_1, L_2, L_3\}, \quad L_1, L_2, L_3 > 0 \tag{16}$$

then the observer (11) is globally asymptotically stable.

Proof: For the disturbance observer of SUAV MIMU/GPS integrated navigation system, a Lyapunov function candidate for the observer can be chosen as

$$V(\boldsymbol{e}) = \boldsymbol{e}^T \boldsymbol{L}\boldsymbol{e} \tag{17}$$

Differentiating the Lyapunov function with respect to time t along the observer trajectory gives

$$\begin{aligned} \frac{dV(\boldsymbol{e})}{dt} &= \frac{\partial V(\boldsymbol{e})}{\partial \boldsymbol{e}}\dot{\boldsymbol{e}} \\ &= -\boldsymbol{e}^T(\boldsymbol{L}^T + \boldsymbol{L})\boldsymbol{L}\boldsymbol{e} \\ &= -2\boldsymbol{e}^T\boldsymbol{L}^2\boldsymbol{e} \end{aligned} \tag{18}$$

Hence, $V(\boldsymbol{e}) > 0, (dV(\boldsymbol{e})/dt) < 0$ for all $\boldsymbol{e}$ if $\boldsymbol{L}$ satisfies (16). For the Theorem, the stability of the observer depends on the $L_i (i = 1 \sim 3)$. By choosing the design parameter $L_i (i = 1 \sim 3)$ satisfying the inequality (16), the global stability of the observer is guaranteed.

4. Design of the Anti-interference Filter

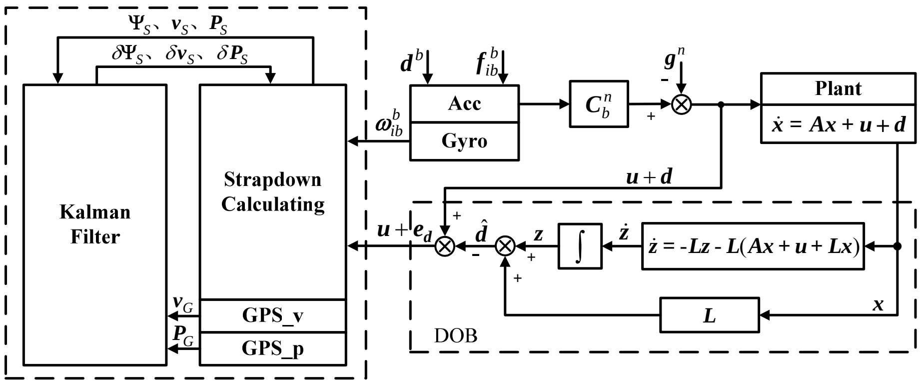


Fig. 3 The anti-interference filter of SUAV integrated navigation system

According to the disturbance observer (11), the design of anti-interference filter structure is shown in figure 3. In the graph, there are two levels of the anti-interference filter of the integrated navigation system. The first level is the disturbance observer, which estimates and compensates the low frequency and variable-mean interference components in MEMS devices; and the second level is the Kalman filter, which suppresses the Gauss white noise in the system. The system is a MIMO system. The input signal includes: gyroscope signal and accelerometer signal $\mathbf{Gyro} = [\,G_x^b \quad G_y^b \quad G_z^b\,]^T$, $\mathbf{Acc} = [A_x^b \quad A_y^b \quad A_z^b]^T$, GPS position signal and GPS speed signal $\mathbf{P}_G = [\,L_G \quad \lambda_G \quad h_G\,]^T$, $\boldsymbol{v}_G = [V_{GE} \quad V_{GN} \quad V_{GU}\,]^T$. System output the results of MIMU/GPS integrated navigation anti-interference filter, including: system position and system velocity $\mathbf{P} = [L \quad \lambda \quad h]^T$, $\boldsymbol{V} = [V_E \quad V_N \quad V_U\,]^T$.

Due to the introduction of vibration interference, the accelerometer signal with interference are expressed as $\mathbf{A\tilde{c}c} = \mathbf{Acc} + \boldsymbol{d}^b$. Firstly, $\mathbf{A\tilde{c}c}$ should be compensated by gravity acceleration $\boldsymbol{g}^n$ after its transformation from carrier coordinate system; then the equivalent control of the velocity is obtained, which is expressed as $\boldsymbol{u}+\boldsymbol{d}$. And $\boldsymbol{u}+\boldsymbol{d}$ is also the equivalent control of the system. According to the disturbance observer state model (1), system status $\boldsymbol{x}$ is disturbed by interference $\boldsymbol{u}+\boldsymbol{d}$. We use $\boldsymbol{x}$ as the input of the disturbance observer (11), then the observer outputs disturbance estimator $\hat{\boldsymbol{d}}$. After $\boldsymbol{u}+\boldsymbol{d}$ is compensated by $\hat{\boldsymbol{d}}$, the equivalent control $\boldsymbol{u}+\boldsymbol{e}_d$ can be obtained. Where, $\boldsymbol{e}_d$ is the disturbance compensation error. Then use $\boldsymbol{u}+\boldsymbol{e}_d$ and gyroscope output data to carry out the strapdown calculation. Finally we can use the result of the strapdown calculation, the GPS data to complete the anti-interference calculation of integrated navigation filter.

5. Vibration Table Experiment

The MIMU/GPS integrated navigation system is fixed on the vibration table through the fixture. In order to simulate the vibration environment of the SUAV, the vibration parameters are set as shown in Figure 1. Set each vibration experiment longer than 30min. The anti-interference filtering algorithm and the traditional Kalman combination filter algorithm are compared in this vibration test. During the experiment, the system outputs integrated navigation data; and the data acquisition and storage processes are achieved by specific designed software.

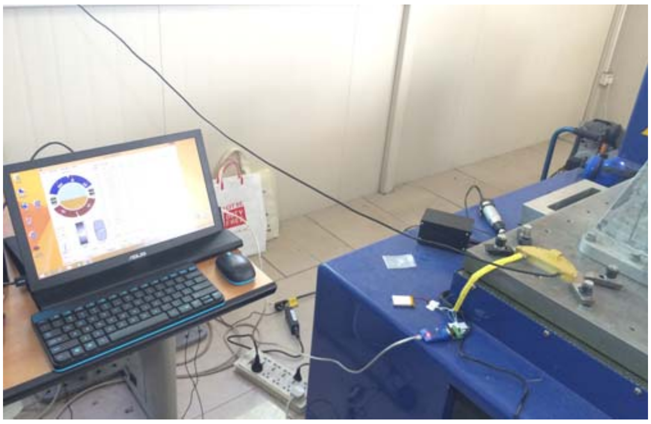
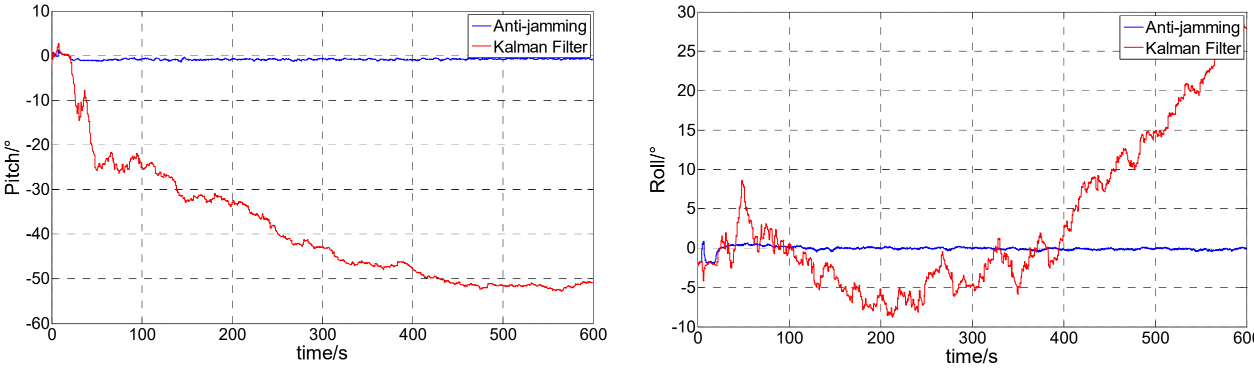


Fig. 4 The vibration table experiment of integrated navigation system

Experimental contrast curves are shown in Figure 5. The traditional Kalman combination filter curve rapidly diverged. In 600s, the pitching angle quickly spread to -50°, and the rolling angle spread to 25°. And, the attitude angle of the integrated navigation system is kept small fluctuations in the anti-interference integrated filter curve. Pitching angle fluctuation range is -1.5°~0.4°, rolling angle fluctuation range is -0.5°~0.6°. The MIMU/GPS system, based on the operation of anti-interference filtering algorithm, keeps a more accurate and stable attitude angle in the vibration environment. The system keeps the normal operation after the vibration ceased.

The experimental results show that traditional Kalman filter is difficult to resist the complex vibration interference caused by vibration table. So it can be concluded that the usage of traditional Kalman filter will lead to the precision decline of the navigation system and even the filter divergence. While, the anti-interference filtering method can effectively estimate and compensate the low frequency and variable-mean interference components in MEMS devices, and effectively suppress the Gauss white noise vibration interference in the system by combing with Kalman Filter. So equipped with this novel filter will maintain the stability of the navigation system among complicated environment, effectively improve the accuracy and anti-interference capability of the MIMU/GPS integrated navigation system.



(a) Pitching angle (b) Rolling angle

Fig. 5 The vibration table experiment contrast curve of integrated navigation system

6. Summary

1) Low altitude and long endurance SUAV vibration signal has the characteristics of multi-source, wide-band and non-stationary. The vibration severely influences the precision of the MIMU/GPS integrated navigation system and even causes the divergence of the filter.

2) In this paper, a filtering method for the vibration disturbance of integrated navigation system is proposed. By using the design idea of DOB, the low frequency variable-mean interference signal can be effectively estimated in MEMS device.

3) Compared with the traditional Kalman filtering method, the anti-interference filtering method of the MIMU/GPS integrated navigation system increases the complexity of the system.

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