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Reference information time delay estimation and compensation in transfer alignment

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Abstract: To reduce the error in transfer alignment caused by reference information delay, a time delay estimation method is developed based on least-squares curve fitting of the angular rate integration. First, the gyro sensor measurements of the main strapdown inertial navigation system (M-SINS) and the slave strapdown inertial navigation system (S-SINS) are recorded for a few seconds and the integration of the data is calculated. Then, the possible maximum range of the delay value is defined and the points of the curve at different intervals are moved. The square of the differences between the corresponding points are calculated. Finally, the delay estimation can be acquired by the least-squares curve fitting of the M-SINS and the S-SINS. A delay compensation method by local data shifting is also presented. The simulation results demonstrate the effectiveness of delay estimation and indicate that the estimation accuracy is independent of the delay value. And the local data shifting compensation method can effectively reduce the errors of the transfer alignment caused by the reference information delay.

Key words: transfer alignment; delay; estimation; compensation; synchronization; least squares; curve fitting

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The design of transfer alignment algorithms for tactical missiles has been an area of intense research due to the targeting accuracy dependency upon them. Different matching methods are implemented on various kinds of moving platforms and dynamic conditions. Information such as velocity, altitude, position and angular rate is transmitted by the reference strapdown inertial navigation system (M-SINS) to the slave strapdown inertial navigation system (S-SINS). During transmission parameters such as bus arbitration, RAM access, addressing, electro magnetic interference, coding, decoding and modulation can cause transmission delay.

Time delay may cause some misalignment between the M-SINS and S-SINS, which can reduce the accuracy of the transfer alignment. So it is necessary to synchronize the data between different navigation systems. A commonly used time delay estimation method is to add a delay variable to the Kalman filter state vector. But the Kalman filter is a state estimator based on the statistic characteristics of the state vector which needs to be predefined. It is not adaptive to different dynamic conditions and systems.

In this paper, a time delay estimation method based on the least-squares curve fitting algorithm is presented. The estimated time delay is compensated for by S-SINS data shifting. The effectiveness of the delay estimation and compensation algorithm is demonstrated by simulation results.

1 Commonly Used Delay Estimation Method

To reduce the impact of transmission time delay, different methods are implemented. The commonly applied delay estimation methods are as follows:

1) Kalman filter estimation

Time delay can be added to the state vector of the Kalman filter. During iterations, the measurements will update the time delay estimation. The delay impact is compensated for during the iteration. But time delay is coupled with the whole state vector before the filter converges. The time delay model and the statistical characteristics should be precisely known and pre-defined.

2) Adding time stamp to communication data package[1]

Some modern communication protocols have time stamps in the data package which can be used to synchronize different systems which work on the bus. But the command execution time of most computer systems, even real-time operation systems, is unpredictable. The bus arbitration time and the sensor sampling time are not considered, but they cannot be ignored.

3) Direct measurement by two-way communication[2]

Time delay can be accurately measured by special equipment if two-way communication is established. Time delay can be stored and compensated for in operation. But time delay is both hardware and software dependent. Due to different communication priorities, every sub system has different time delays. And if any modification has been made to the software or hardware, measurements should be carried out again.

4) Hardware synchronization[3]

Hardware synchronization means sending the trigger signal simultaneously to all the sensor sampling systems. Combined with time stamps of the data package, it is an effective way to align the sensor measurements. To realize this, additional controller and communication channels are required. For the existing system, it is not easy to make an update.

Thus, it is necessary to develop a method which is adaptable to different applications and can be quickly and easily implemented to existing systems.

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2 Delay Estimation Based on Least-Squares Curve Fitting

Fig. 1 illustrates the misalignment of the two curves caused by the reference information delay. In order to avoid the delay impact, synchronization of the two INSs can be realized by moving one of them forward or backward.

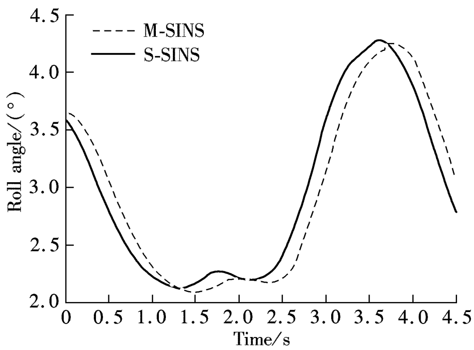

Fig. 1 Local calculated roll angle and delayed reference information

Position, velocity, altitude and sensor measurements are chosen to calculate the time delay. Ideally, the data which is chosen should not be dependent on the reference system and can be acquired as soon as the SINS powers on. It should change quickly enough.

The S-SINS and the M-SINS are installed on the same carrier. Suppose that the carrier frame is perfectly rigid and the M-SINS and the S-SINS are precisely aligned. The gyro sensor measurements curves of the M-SINS and the S-SINS have the same shape and amplitude. But in practice, the flexure is normally not ignorable. It is not practical to simply compare the angular rates. But integration has a smoothing effect and will reduce the impact of the high frequency flexure. So it is possible to compare the integration of the gyro measurements of the M-SINS and the S-SINS.

A new time delay estimation method is designed with the following procedures:

1) Record the data of both the M-SINS and the S-SINS for a certain period, e. g. 5 s, and N data points are saved;

2) Define the value of the possible maximum time delay, e. g. 1 s;

3) Calculate the integration of the angular rate,

$$\boldsymbol{I}_i(t) = \int_0^{T_t} \omega_i(t)\,\mathrm{d}t \tag{1}$$

And the following equation in the discrete system is applied,

$$\boldsymbol{I}_i(j) = \sum_{k=0}^{j} \omega_i(k)\, t_s \tag{2}$$

where $i = x, y, z$; $j = 0, 1, 2, \cdots, N-1$; t_s is the sensor sampling interval.

4) Move the curve of the M-SINS backward and calculate the square of the difference of every data point on the curve.

$$\mathrm{sum}(n) = \sum_{i=0}^{N-1} \{ [I_{1_M}(i+n) - I_{1_s}(i)]^2 + [I_{2_M}(i+n) - I_{2_s}(i)]^2 + [I_{3_M}(i+n) - I_{3_s}(i)]^2 \} \tag{3}$$

5) Calculate the minimum value of the results in step 4) and t_{delay}.

$$\mathrm{sum}(n_t) = \min\ \mathrm{sum}(n) \tag{4}$$

$$t_{\mathrm{delay}} = t_s n_t \tag{5}$$

where t_{delay} is the delay time.

The application of this algorithm is not suitable for very low amplitudes and periodical signals. Calculating the mean value and variance can recognize such kinds of signals. But one special case should be considered:

$$\int_0^{T_t} \omega_1(t+T)\,\mathrm{d}t + \int_0^{T_t} \omega_2(t+T)\,\mathrm{d}t + \int_0^{T_t} \omega_3(t+T)\,\mathrm{d}t = \int_0^{T_t} \omega_1(t)\,\mathrm{d}t + \int_0^{T_t} \omega_2(t)\,\mathrm{d}t + \int_0^{T_t} \omega_3(t)\,\mathrm{d}t \tag{6}$$

where T is less than the assumed maximum time delay.

In this case, the frequency and the phase of the three angular rates in the whole sampling period should be identical. The probability of such a case is low in practice. Spectrum analysis and further restriction can be applied.

3 Delay Compensation

The time delay compensation method proposed in Refs. [4 − 7] are mainly based on extrapolation or interpolation. A short-term model is built to predict the current value. For example, the first-order derivative is used to describe the changing rate:

$$X(k) = X(k-\Delta t) + X(k-\Delta t)\Delta t \tag{7}$$

This is, in fact, using the already known values to predict the future values. The prediction accuracy is highly model-dependent. In practice, it is very difficult to obtain a perfect model of the system.

The purpose of delay compensation is to keep the data aligned as well as possible. There is no real-time output during the process. The transfer alignment is used to keep the coordinates of the M-SINS and the S-SINS aligned and to estimate the sensor errors of the S-SINS. If the time delay has been already estimated, it is possible to move the S-SINS information backward instead of making a one-step ahead prediction of the M-SINS information (see Fig. 2).

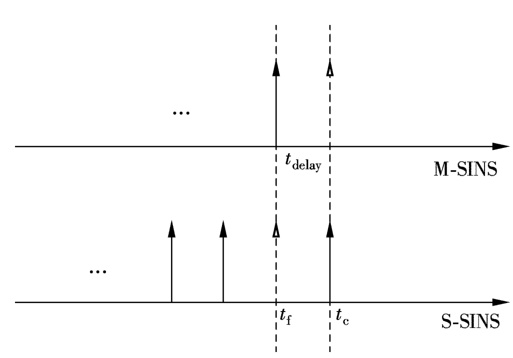

Fig. 2 Transmission delay compensation by local data shifting

4 Simulation Conditions

To simulate the impact of reference information time delay and to evaluate the delay estimation and compensation algorithm, the simulation is carried out under the following conditions.

Assume that an aeroplane is traveling at an altitude of 1 000 m at an initial speed of 200 m/s. The initial position is 32°N, 118°E. There is no error in the M-SINS gyro outputs. The constant drift of the S-SINS gyroscope is 1°/h, and the bias of the accelerometer is $0.2\times10^{-3}g$. The random noise of the S-SINS gyroscopes and accelerometers are $N(0,(1°/\mathrm{h})^2)$ and $N(0,(0.2\times10^{-3}g)^2)$, respectively. The S maneuver will start from the 150th second (see Fig. 3).

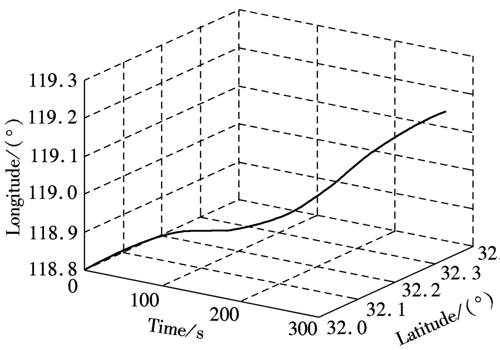

Fig. 3 Trajectory of aeroplane in simulation (S maneuver)

The "velocity + altitude" matching is applied in transfer alignment[8]. Set up the Kalman filter with the system state vector:

$$\boldsymbol{X}=[\boldsymbol{\varphi}^{n\mathrm{T}}\quad \delta\boldsymbol{V}^{n\mathrm{T}}\quad \boldsymbol{\varepsilon}^{b_s\mathrm{T}}\quad \nabla^{b_s\mathrm{T}}\quad \boldsymbol{\mu}^{b_f\mathrm{T}}\quad \boldsymbol{\lambda}_{\mathrm{f}}^{b_m\mathrm{T}}\quad \boldsymbol{\omega}_{\mathrm{f}}^{b_m\mathrm{T}}]^{\mathrm{T}}$$

where $\delta\boldsymbol{V}^n$ is the S-SINS velocity error; $\boldsymbol{\varphi}^n$ is the altitude error; ∇^{b_s} is the accelerometer bias; $\boldsymbol{\varepsilon}^{b_s}$ is the gyro drift; $\boldsymbol{\mu}^{b_f}$ is the S-SINS mounting error; $\boldsymbol{\lambda}_{\mathrm{f}}^{b_m}$ is the flexure angle and $\boldsymbol{\omega}_{\mathrm{f}}^{b_m}$ is the flexure angular rate. The system equations are

$$\left.\begin{aligned}
&\delta\boldsymbol{V}^n=(\boldsymbol{C}_{b_s}^n f^{b_s})\boldsymbol{\varphi}^n-(2\boldsymbol{\omega}_{ie}^n+\boldsymbol{\omega}_{en}^n)\delta\boldsymbol{V}^n+\boldsymbol{C}_{b_s}^n\nabla^{b_s}+\boldsymbol{C}_{b_s}^n\nabla_{\mathrm{w}}^{b_s}\\
&\boldsymbol{\varphi}^n=-\boldsymbol{\omega}_{in}^n\boldsymbol{\varphi}^n-\boldsymbol{C}_{b_s}^b\boldsymbol{\varepsilon}^{b_s}-\boldsymbol{C}_{b_s}^b\boldsymbol{\varepsilon}_{\mathrm{w}}^{b_s}\\
&\boldsymbol{\varepsilon}^{b_s}=\boldsymbol{0}\\
&\nabla=\boldsymbol{0}\\
&\boldsymbol{\mu}^{b_f}=\boldsymbol{0}\\
&\boldsymbol{\lambda}_{\mathrm{f}}^{b_m}=\boldsymbol{\omega}_{\mathrm{f}}^{b_m}\\
&\boldsymbol{\omega}_{\mathrm{f}}^{b_m}=-[\boldsymbol{\beta}^2]\boldsymbol{\lambda}_{\mathrm{f}}^{b_m}-2[\boldsymbol{\beta}]\boldsymbol{\omega}_{\mathrm{f}}^{b_m}+\boldsymbol{\eta}
\end{aligned}\right\}\tag{8}$$

where $\boldsymbol{C}_{b_s}^n$ is the transformation matrix from the S-SINS to the navigation coordinates; $\boldsymbol{C}_b^{b_s}$ is the transformation matrix from the carrier body to the S-SINS; $\nabla_{\mathrm{w}}^{b_s}$ is the accelerometer instrument error vector; $\boldsymbol{\varepsilon}_{\mathrm{w}}^{b_s}$ is the gyro drift error vector; $\boldsymbol{\beta}$ is the flexure model parameter; $\boldsymbol{\eta}$ is the Gauss white noise. The discrete step is 0.05 s, and the filter iteration interval is 1 s. The simulation work flow is illustrated in Fig. 4.

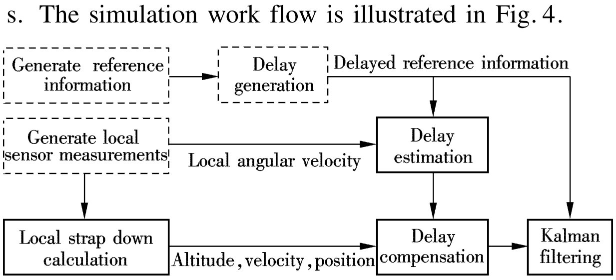

Fig. 4 Simulation flowchart

5 Simulation Results

In the simulation, the reference information delay is generated by moving the curve forward along the time axis. Different delay values are generated and tested. The maximum delay is set up to 1 s. The time delay is estimated from the local and reference data of 5 s duration.

The simulation results are listed in Tab. 1 and Tab. 2. The estimation accuracy is independent of time delay and is less than 5 ms (one data point).

Tab. 1 Simulated delay and estimation

Simulation number	1	2	3	4
Simulated delay/ms	10	50	100	150
Shifted points	2	10	20	30
Estimated delay/ms	10	50	100	150

Tab. 2 Heading error standard deviation (°)

Delay/ms	0	10	50	100	150
Without compensation	3.2	5.3	20.6	40.7	60.9
With compensation	3.2	3.2	3.2	3.2	3.2

Fig. 5 illustrates the impact of reference information delay. From Fig. 5, we can see that the transfer alignment matching method "velocity + altitude" is sensitive to reference information time delay.

By the compensation algorithm with an estimated delay value, we can obtain the curves shown in Fig. 6. The impact of the reference information time delay has been greatly reduced.

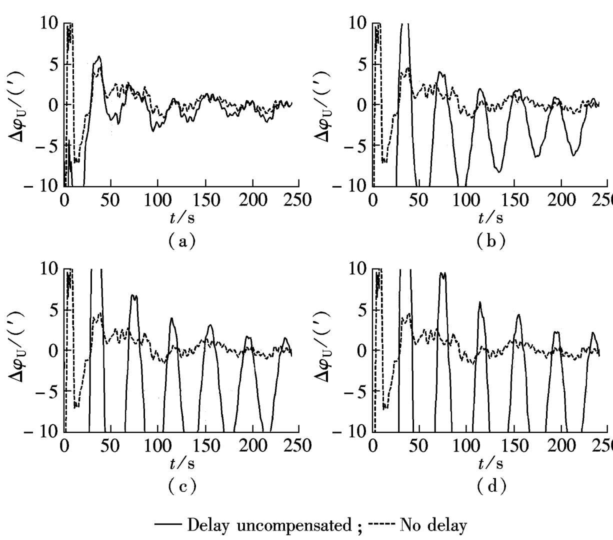

Fig. 5 Heading estimation error (delay uncompensated). (a) $t_{\mathrm{delay}}=10$ ms; (b) $t_{\mathrm{delay}}=50$ ms; (c) $t_{\mathrm{delay}}=100$ ms; (d) $t_{\mathrm{delay}}=150$ ms

6 Conclusion

In this paper, a new method for reference information time delay estimation based on the least-squares curve fitting of angular rate integration and the delay compensation method by local data shifting are presented. The simulation results demonstrate the effectiveness of the methods.

The application of the estimation method is restricted when the measurements of all three gyro sensors have the identical period and initial phase. A distinguishing method of periodical signal can be added to disable the estimation in such conditions.

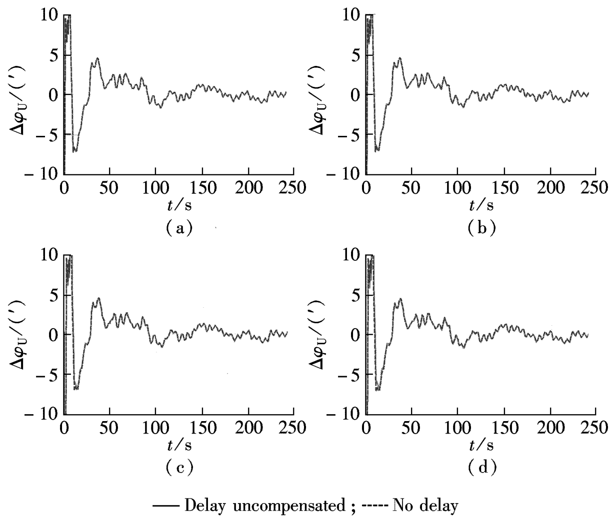

Fig. 6 Heading estimation error (delay compensated). (a) t_{delay} = 10 ms; (b) t_{delay} = 50 ms; (c) t_{delay} = 100 ms; (d) t_{delay} = 150 ms

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传递对准中基准信息时间延迟的估计与补偿

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摘要:针对传递对准过程中基准信息时间延迟对传递对准精度的影响,给出了一种基于角速率积分最小方差曲线拟合的时间延迟估计方法. 首先,记录一段时间内主、子惯导陀螺传感器的输出数据,并对该数据进行积分. 然后,定义基准信息可能存在的时间延迟的最大范围,并在该范围内对主惯导数据进行逐点移位,计算曲线各对应点的差的平方并求和. 最后,通过最小方差法求主、子惯导传感器数据曲线的最佳拟合,从而获得基准信息时间延迟. 同时,给出了一种本地数据移位的延迟补偿算法. 数学仿真证明了角速率积分最小方差曲线拟合的时间延迟估计方法的估计精度较高,并且跟时间延迟大小无关. 本地数据移位的延迟补偿方法可以有效降低基准信息时间延迟对传递对准精度的影响.

关键词:传递对准;延迟;估计;补偿;同步;最小方差;曲线拟合

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