SAR MOTION INFORMATION SENSOR BASED ON GNSS/SINS

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Abstract Synthetic aperture radar (SAR) is theoretically based on uniform rectilinear motion. But in real situations, the flight cannot be kept in a uniform rectilinear motion due to many factors. Therefore, the motion compensation is needed to achieve the high-resolution image. This paper proposes an improved motion information sensor (MIS)-based on global navigation statellite system (GNSS) and strapdown inertial navigation system (SINS) for SAR motion compensation. MIS can provide the long-term absolute accuracy, and the short-term high relative accuracy during SAR imaging. Many issues related to MIS, such as system design, error models and navigation algorithms, are stressed. Experimental results show that MIS can provide accurate navigation information (position, velocity and attitude) to meet the requirements of SAR motion compensation. Especially, MIS is suitable for the case: the accuracy of airplane master inertial navigation system is too low or not configured.

Key words: integration navigation; Kalman filter; SAR; motion compensation

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INTRODUCTION

Synthetic aperture radar (SAR) is an imaging radar system that utilizes aircraft motion and signal coherency to allow the formation of a synthetic aperture, which is much longer than the real antenna. The SAR technology, with the ability of all weather and high resolution, has already been used in many areas[1,2], such as deformation monitoring, ocean or forest environment monitoring. Over last thirty years, different types of SAR systems have been developed, e.g. airborne SAR systems and spaceborne SAR systems.

SAR is based on uniform rectilinear motion theoretically. However, due to air turbulence, high-altitude winds and other factors, it is difficult to maintain the flight in a uniform rectilinear motion. Without compensations, these factors would have serious effects on the SAR imaging, even the image cannot be obtained.

The motion information sensor is used to determine the accurate precise position of radar antenna phase center (APC) relative to target during the SAR imaging interval, and derive the displace of APC along radar line-of-sight (LOS) direction with time. Many different motion sensing system configurations have been studied in the past thirty years in SAR compensation. In all the methods[3-6], the aircraft′s master inertial navigation system (MINS) is needed for the antenna motion data. Block diagram of these methods can be described in Fig. 1. A transfer

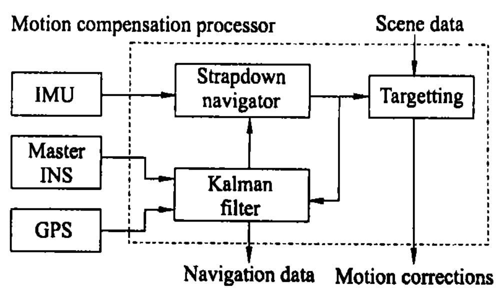

Fig. 1 Block diagram of MIS aided by MINS

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alignment Kalman filter is used to align the slaved strapdown navigator's computed local horizontal frame with the high accuracy MINS' computed local horizontal frame. But in some cases, the accuracy of MINS of some airplanes is too low to meet the requirements of SAR motion compensation.

This paper describes an improved motion information sensor (MIS) for the airborne SAR imaging systems. MIS is based on the integration of GNSS and SINS to provide precise position, velocity and attitude of the SAR antenna.

1 DESIGN OF GNSS/SINS MIS

1.1 Specification of SAR motion information sensor

The system requirements for the SAR image compensation are quite different from conventional navigation systems. For conventional navigation systems, the absolute accuracy of the system is the most important. However, the accuracy requirements for MIS depend on the different work periods of SAR system. Firstly, MIS should provide highly accurate position and velocity for all flight phases, with the horizontal position accuracy of smaller than 10 m, and attitude accuracy of less than 2 mill-radians (0.1°). During imaging interval (typical 40 s), the relative positions of the APC motion should be determined with high precision in order to obtain high quality images. All the navigation information of MIS should not have any large jumps, e.g. the discontinuity of position must be smaller than 10 mm. The position and the velocity are sent to SAR processor to compensate the aircraft's parallel motion. Attitudes are sent to antenna servo platform to control and stabilize the attitude of the antenna.

1.2 Overall functional block of MIS

Using GNSS/SINS integrated system in MIS can provide high absolute position accuracy. It is well known that the motion information of the integrated system often has a large jump before and after measurement update. The discontinuity of position estimates from the integrated system can be much larger than 10 mm, or even meters[7]. So the output of integrated navigation system cannot be used directly in SAR motion compensation during imaging intervals.

In order to satisfy the both absolute and relative positioning requirements, MIS runs two different modules. The overall functional block of GNSS/SINS integrated motion information system is shown in Fig. 2. Part 1 is used to provide relative motion information during imaging intervals, while Part 2 integrates GNSS and SINS to provide the absolute motion information. System software runs in two different frequencies: SINS modules (Module 1 and Module 2) run with a rate of 50 Hz while Kalman filter of the integrated system runs with 1 Hz. The real time of the pure inertial navigation algorithm (Part 1) is less than 1 ms, and the Kalman filter algorithm (Part 2) is less than 19 ms.

The processing procedure of MIS is controlled by the pulse signal and sent out by SAR master computer. The procedure can be described as follows:

(1) From aircraft taking off to imaging, MIS works on the normal integrated mode. Switch k is turned off, and switch c is turned to b. The information of Part 2 is sent out to SAR.

(2) Receiving the pulse to image, switch k is turned on, switch c is turned to a, the SINS module 1 is initialized by SINS module 2. The initial position and velocity of SINS module 1 come from SINS module 2, and some middle temporary parameters, such as attitude matrix, also come from SINS module 2. Then Part 1 starts to work on a stand-alone SINS mode and output the motion information to the SAR system for relative motion compensation, while Part 2 continues

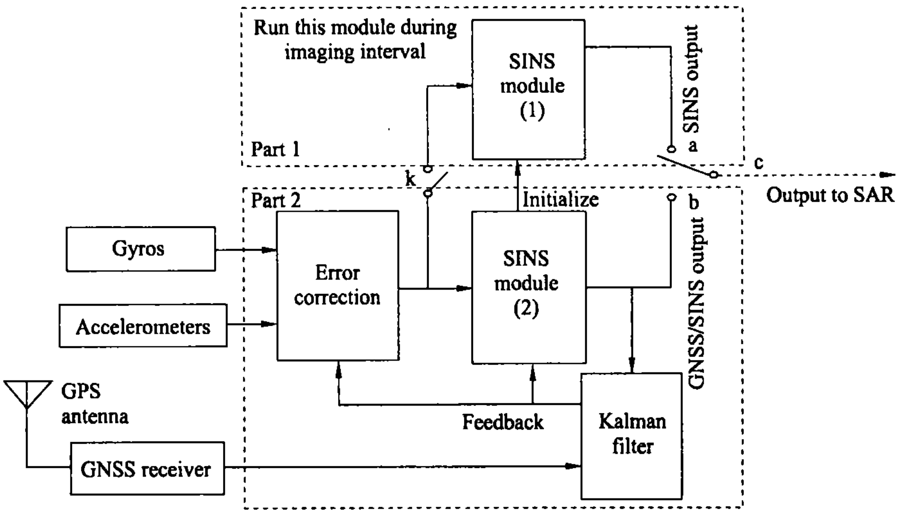

Fig. 2 Overall functional block of SAR MIS without MINS

(3) From SAR imaging, navigation computer starts to calculate the imaging time. If MIS does not receive pulse signal in given time period (e.g. 50 s), Part 1 will stop working, while Part 2 continues. Switch k is turned off, and switch c is turned to b. MIS works on the normal integrated mode as step 1.

1.3 Models and algorithm of GNSS/SINS MIS

According to the method of the correction of the system, there are two kinds of Kalman filter: Open-loop correction (namely output correction) and closed-loop correction (namely feedback correction). Open-loop correction is easy to be realized and the errors of the filter do not influence on all inertial navigation systems. But the error of INS is increased with the time. The mathematical model of the Kalman filter is founded under the assumed condition that the error of the system is small enough for the first-order shear deformation plate theory. After running for a long time, the SINS error is no longer small, then model error will occur in filter equations and the accuracy of the filter will be decreased. On the other hand, to the closed-loop correction, the error of the system is maintained to be small enough, and the filter equations have no model errors. The closed-loop correction is more difficult to be realized than open-loop correction, and the errors of the filter influence on the output of SINS. To achieve high precise filter accuracy, a closed-loop correction is used in MIS.

The navigation algorithm for the integration of GNSS and SINS is based on 12 states closed-loop Kalman filter[8]. The error states include navigation information errors and IMU errors. The position and velocity derived from GNSS receiver are used to update the Kalman filter. The dynamic error model of the integrated GNSS/SINS can be written as

$$
\begin{aligned}
\dot{\boldsymbol{X}}(t) &= \boldsymbol{F}(t)\boldsymbol{X}(t) + \boldsymbol{G}(t)\boldsymbol{W}(t) + \boldsymbol{B}(t)\boldsymbol{U}(t) \\
\boldsymbol{Z}(t) &= \boldsymbol{H}(t)\boldsymbol{X}(t) + \boldsymbol{V}(t)
\end{aligned}
\tag{1}
$$

where

$$
\boldsymbol{X} = [\phi_N, \phi_E, \phi_D, \Delta v_N, \Delta v_E, \Delta v_D, \Delta L, \Delta\lambda, \Delta h, \varepsilon_{rx}, \varepsilon_{ry}, \varepsilon_{rz}]^T
$$

ϕ_N, ϕ_E, ϕ_D are the 3D platform angle errors; $\Delta v_N, \Delta v_E, \Delta v_D$ the 3D velocity errors; $\Delta L, \Delta\lambda, \Delta h$ the 3D position errors and $\varepsilon_{rx}, \varepsilon_{ry}, \varepsilon_{rz}$ the gyro first-order Markov drift errors. $\boldsymbol{F}(t)$ is the state transition, $\boldsymbol{G}(t)$ the coefficient matrix, $\boldsymbol{B}(t)$ the control matrix, $\boldsymbol{H}(t)$ the measurement matrix, $\boldsymbol{W}(t)$ the dynamics noise and $\boldsymbol{V}(t)$ the measurement noise.

The closed loop discrete-time Kalman filter is summarized as

$$
\begin{cases}
\hat{X}(k/k-1) = \Phi(k,k-1)\hat{X}(k-1/k-1) + \\
\qquad B(k,k-1)U(k-1) \\
\hat{X}(k/k) = \hat{X}(k/k-1) + K(k)[Z(k) - \\
\qquad H(k)\hat{X}(k/k-1)] \\
K(k) = P(k/k-1)H^{T}(k)[H(k)P(k/k-1)\cdot \\
\qquad H^{T}(k) + R(k)]^{-1} \\
P(k/k-1) = \Phi(k,k-1)P(k-1/k-1)\cdot \\
\qquad \Phi^{T}(k,k-1) + \Gamma(k,k-1)Q(k-1)\cdot \\
\qquad \Gamma^{T}(k,k-1) \\
P(k/k) = [I - K(k)H(k)]P(k/k-1)\cdot \\
\qquad [I - K(k)H(k)]^{T} + \\
\qquad K(k)R(k)K^{T}(k)
\end{cases}
\tag{2}
$$

If feedback controls are added to all the state vectors, $B(k)$ of Eq. (2) will be the unit matrix, and then feedback control vector $U(k)$ will be considered as

$$U(k) = -\Phi(k+1,k)\hat{X}(k/k) \tag{3}$$

Details of the algorithm can be found in Ref. [8].

The optimal control rule has been derived from Eqs. (2, 3). But how to realize the feedback control rule $U(k)$ physically? To different variables, the realization methods are different. The methods used in this paper are described as follows.

(1) Correction directly to the velocity and position. To the errors of velocity and position, the value of every epoch is the original value for the next epoch integration. Therefore, the control rule U can be directly used to correct the errors of these variables (written as P)

$$P^{+} = P^{-} + U \tag{4}$$

where P^{-} is the state before correction and P^{+} the state after the correction.

(2) Correction to the SINS platform angle errors. There are several methods to correct the errors of platform angles. In this paper, the SINS platform error angles (φ_N, φ_E, φ_D) are transferred to attitude and heading errors ($\Delta\gamma$, $\Delta\theta$, $\Delta\psi$) as Eq. (5), and then correct attitude and heading angles to get attitude angles (γ, θ) and heading ψ as Eq. (6).

$$
\begin{bmatrix} \Delta\gamma \\ \Delta\theta \\ \Delta\psi \end{bmatrix} =
\begin{bmatrix} \cos\psi/\cos\theta & \sin\psi/\cos\theta & 0 \\ -\sin\psi & \cos\psi & 0 \\ \cos\psi\,\mathrm{tg}\theta & \sin\psi & 1 \end{bmatrix}
\begin{bmatrix} \varphi_N \\ \varphi_E \\ \varphi_D \end{bmatrix}
\tag{5}
$$

$$
\begin{aligned}
\gamma^{+} &= \gamma^{-} + \Delta\gamma \\
\theta^{+} &= \theta^{-} + \Delta\theta \\
\psi^{+} &= \psi^{-} + \Delta\psi
\end{aligned}
\tag{6}
$$

where γ^{-}, θ^{-}, ψ^{-} are the state before correction and γ^{+}, θ^{+}, ψ^{+} the state after the correction.

(3) Correction to IMU errors. All the corrections of IMU errors, such as gyros drift errors, accelerometers errors, estimated from Eq. (3), writen as $U(i)$, should be added up and then correct IMU errors. That is to say, the correction $V(k)$ of every epoch k is

$$V(k) = \sum_{i=0}^{k} u(i) \tag{7}$$

2 PERFORMANCE TEST

2.1 Static test

Both static and dynamic tests have been conducted to evaluate the performances of MIS.

The long-term accuracy is evaluated based on the static test. During the test, MIS is located at a known location. As the system is not moving, the speed and acceleration output should be zero. Thus the errors of MIS can be easily determined. The test lasted 1 h and the results are shown in Table 1.

Table 1 MIS errors in static test

State variable	Error
Pitch and roll	$< 0.01^{\circ}$
Azimuth	$< 0.05^{\circ}$
Horizontal velocity	< 0.02 m/s
Vertical velocity	< 0.25 m/s
Horizontal position	< 10 m
Altitude	< 25 m

Above error data show that MIS can achieve high precision under the static state.

2.2 Real flight-test

During the real flight, MIS sents the navigation data as an output to the SAR according to the SAR imaging pulse while sending the integrated navigation data to data-recorder all the time for off-line processing. Fig. 3 is a flight curves reckoned by MIS during a certain flight-test, the flight altitude is 4 000m, as shown Fig. 4. Compared with the flight curves reckoned by aircraft master navigation system, the curves of MIS are equivalent to the real flight curves.

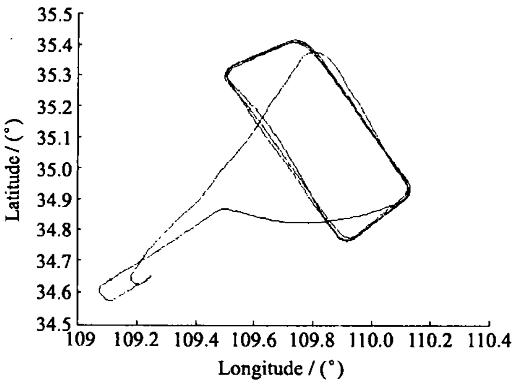

Fig. 3 Flight-test curves reckoned by MIS

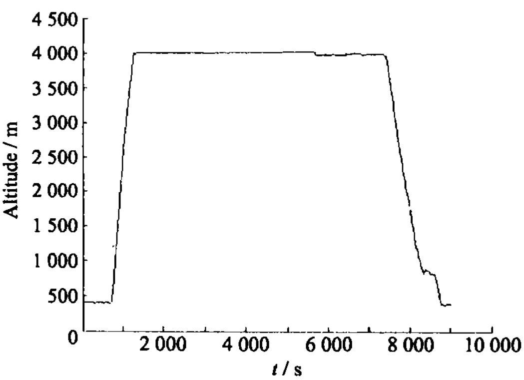

Fig. 4 Flight-test altitude reckoned by MIS

3 CONCLUSION

An improved integrated algorithm of motion information sensor for SAR motion compensation has been presented. The system is suitable for both side-looking SAR and the squint-looking SAR. The main function of the system provides precise position, velocity, and attitude of SAR antenna. Position and velocity are sent to SAR for aircraft parallel motion compensation, and the attitude and azimuth are sent to antenna servo platform to control and stabilize the attitude of SAR antenna, and are used for level arm corrections. It can be mounted on the antenna structure near APC. Different tests have been conducted to evaluate the performance of MIS. Results show that MIS can satisfy the accuracy for SAR motion compensation.

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GNSS/SINS组合 SAR运动信息传感器

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摘要: 提出一种不依赖于机载主惯导的 SAR运动信息传感器方案, 即改进的基于 GNSS/SINS组合运动系统。在成像期间, 输出以纯惯性为主的导航信号, 以保证较高的相对定位精度。而 GNSS/SINS组合, 则保证了长时间的绝对定位精度。本文介绍了这种运动传感器的原理和数学模型等, 并对实验结果作了分析。多次实验表明, 本文提出的基于 GNSS/SINS的运动传感器具有很高的精度, 完全满足了 SAR成像的精度要求, 特别适用于没有主惯导或主惯导精度较低的场合。

关键词: 组合导航; 卡尔曼滤波; 合成孔径雷达; 运动补偿
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