Performance Analysis and Architecture Design of Vector-Based Ultra-Tightly Coupled GPS/INS Integration on satellite Faults

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Abstract: GPS vector receive make the tasks of signal tracking and navigation state estimation are integrated into an algorithm which can complement traditional scalar receiver tracking independent and parallel tracking disadvantage. Through integration with INS, the GPS signal in jamming or weak environment based on vector tracking ultra-tightly coupled GNSS/INS integration system has significant advantages. But vector tracking channels are closely linked, each channel signal tracking processes influence each other, if one or several channels are fault, which will induce the positioning error of the integration system and maybe make the normal channel tracking performance decrease or even instant lock. In this paper, we just performance the ultra-tightly coupled GPS/INS centralized architecture base on vector tracking, when a single channel or multiple channels fault occurs, make the integrated system positioning effect were analyzed theoretically， and through simulation and experiment verify the effects of quantitative, at the last, we design a fault-tolerant architecture and use robust H-infinity filter algorithm for Ultra-tightly coupled GPS/INS Integration.

Key-Words: vector tracking, ultra-tightly coupled GPS/INS integration, theoretical performance, GPS fault, fault-tolerant architecture, H-infinity filter

1 Introduction

The Global Positioning System (GPS) relies on the radio-frequency (RF) signals for positioning has been established as a dominant technology to provide location and navigation capabilities with a high reliability and accuracy. And GPS receiver has become a ubiquitous navigation instrument to civilian and military applications. However, despite its success the GPS system suffers from a basic shortcoming. GPS however is still subject to severe performance degradation in signal-degraded, significant dynamics, dense foliage and urban canyon environments. Because of the GPS signals received near the surface of the Earth are extremely weak. RF interference, whether intentional or unintentional, can also easily disrupt GPS availability. As little as 1.5 pico-watts of incident RF interference are capable of disabling a civilian C/A code receiver [1]. The reliability and functionality of the GPS system suffer due to the relative weakness of the GPS signals.

The Inertial Navigation System (INS) is self-contained dead reckoning (DR) navigation systems provide dynamic information through direct measurements from an Inertial Measurement Unit (IMU). According to its measurement principle INS systems provide an autonomous solution for position, velocity and attitude with high data rate and bandwidth[2]. From this point of view an inertial sensor is the optimal choice for most of the applications in navigation and positioning. Its typical error behaviour, however, causes only a short term stability of a high accuracy level. The INS suffers from time-dependent error growth which causes a drift in the solution, thus compromising the long term accuracy of the system. The rate at which navigation errors grow over time is governed predominantly by the accuracy of the initial alignment, errors in inertial sensors and the dynamics of the trajectory followed.

Due to the INS and GPS have strong complementary advantages, and have been a research focus in the integrated navigation areas. The GPS/INS integrated system takes advantage of the complementary attributes of both systems to yield a system that outperforms either single system operating alone. The combination of GPS and INS not only offers the accuracy and continuity in the solution, but also enhances the reliability of the system. GPS, when combined with INS, can restrict INS error growth over time, and allows for online estimation of the sensor errors, while the INS can enhance the reliability and integrity of the system. It can bridge the position and velocity estimates when there is no GPS signal reception or can assist GPS receiver operation when GPS signal is degraded. Ultimately, the navigation solution derived from an GPS/INS system is better than either standalone solution[3].

The exact manner and level at which the systems are fused together varies widely from implementation to implementation. The improvement in performance brought about by the combination of the two systems is largely determined by the exact manner in which they are fused. Some investigators have described that three strategies are used for GPS and INS integration, namely loosely integration, tightly integration, and ultra-tightly (or deep) integration. With the deepening of coupling of GPS and INS, the performance of the intergraded system will be greatly improved. There is no uniform definition of ultra-tightly coupled (UTC) in the international research institutions [4,5], and the UTC is mentioned in this article which is a vector-based tracking UTC GPS/INS system.

The primary advantages of vector-tracking are noise is reduced in all channels making them less likely to enter the non-linear tracking regions; it can operate with momentary blockage of one or more satellites; and it can be better optimized than scalar-tracking approaches. Vector-tracking is also able to improve tracking in weak-signal or jamming environments, especially when integrated with inertial sensors [6]. The vector tracking significant advantage is mainly reflected in the number of satellite tracking more than four and good satellite geometric distribution [7] [8].

The satellite signals are inevitable existence errors in the generation, transmission, processing, and when GPS satellite change may be fault. With the receiver deal with satellites number increase at the same time, this is bound to increase the probability of the satellite channel fault happen. The existing literature on vector tracking GPS/INS UTC system is mostly confined to the anti-jamming and high dynamic adaptability, less research for fault analysis. In this paper, we carry out theoretical research on vector tracking GPS/INS UTC centralized architecture, And the fault mechanism are discussed, when a single channel or multiple channels measurements have fault, we analysis the integrated system positioning performance from theoretic, which can provide a theoretical basis for future research GPS/INS UTC system fault tolerant architecture, fault tolerant filtering algorithm and choose the appropriate satellite constellation.

2 Algorithm and implementation of vector-based GPS/INS UTC centralized architecture

This paper focuses on the research of GPS/SINS UTC based vector tracking, so the difference between the traditional scalar and vector tracking is introduced firstly.

2.1 Scalar and Vector tracking Receiver

2.1.1 Traditional Scalar tracking receiver

Fig.1 shows a block diagram of the traditional scalar receiver architecture. Tracking loops in each channel are used to estimate the pseudorange and pseudorange-rate for each satellite in view of the receiver. The estimated pseudoranges and pseudorange-rates are fed forward to the navigation processor. The navigation processor uses the estimated pseudoranges and pseudorange-rates to estimate the receiver's position, velocity, and clock states[9].

In Fig.1, the flow of information is strictly left to right. No information from the navigation processor is fed back to the tracking loops. Additionally, the tracking loops in each channel operate independently of each other; therefore no information is exchanged between them. Each channel of the receiver tracks its respective signal independent of the other channels. Therefore, the traditional receiver architecture does not exploit the inherent coupling between the receiver's dynamics and the dynamics seen by the tracking loops.

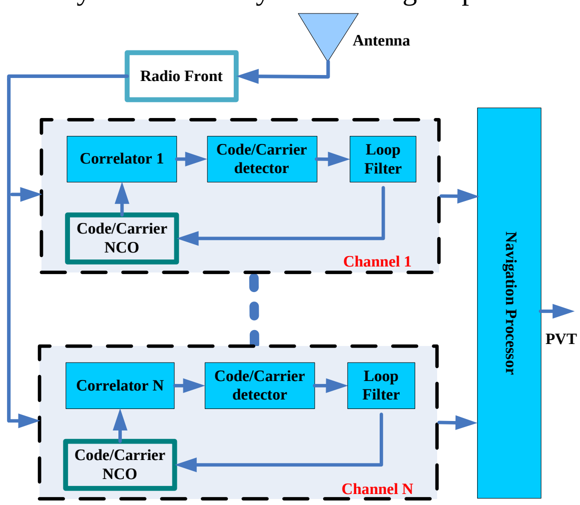

Fig.1 Traditional Scalar Receiver architecture

The benefits of scalar receiver are the relative ease of implementation and a level of robustness that is gained by not having one tracking channel corrupt another tracking channel. However, on the downside, the fact that the signals are inherently related via the receiver's position and velocity is completely ignored. Furthermore, the possibility for one tracking channel to aid another channels is impossible. For more information on scalar-tracking receiver, please refer to the references [10,11].

2.1.2 Vector tracking receiver

Fig.2 shows a block diagram of a vector tracking receiver architecture. For the receiver shown in Fig.2, the tasks of signal tracking and navigation state estimation are no longer separate processes. The single Extended Kalman Filter (EKF) simultaneously tracks the received signals and estimates the receiver's position, velocity, etc. A Vector Delay Lock Loop (VDLL) only tracks the PRN code phases through the central filter. The task of carrier tracking is still handled by scalar tracking loops in each channel in the VDLL. A Vector Delay/Frequency Lock Loop (VDFLL) uses the central filter to track the PRN code phases and the carrier frequencies. The focus of the research in this paper is on the VDFLL.

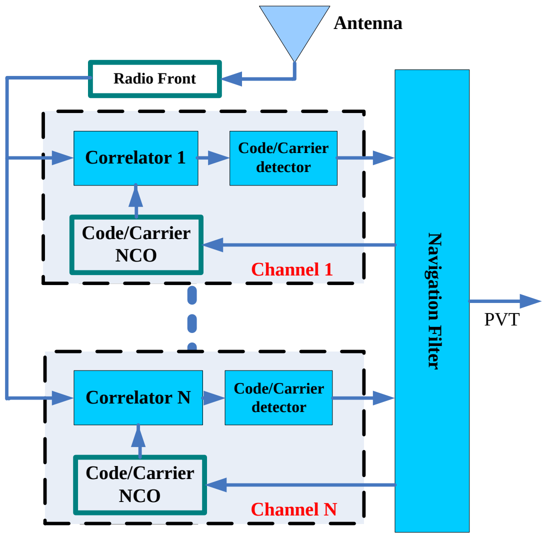

Fig.2 vector tracking receiver architecture

The reason vector tracking is possible relies on the basic nature of the GPS network. The principle behind GPS is that the receiver's position and velocity can be determined based on the phase and frequency of the received signals. Vector tracking algorithms take this basic idea and reverse it. The phase and frequency of the received signals are predicted from the receiver's estimated position and velocity. Residuals are formed in each channel by taking the difference between the predicted and received signals. The residuals are then used to update the estimates of the receiver's position and velocity. The vector tracking approach exploits the coupling between the receiver's dynamics and the dynamics seen by the tracking loops. Instead of every channel of the receiver tracking the dynamics of the individual signals, the user dynamics that are causing the change in the signals are tracked.

The primary advantages of vector-tracking are; noise is reduced in all channels making them less likely to enter the non-linear tracking regions; it can operate with momentary blockage of one or more satellites; and it can be better optimized than scalar-tracking approaches. Vector-tracking is also able to improve tracking in weak-signal or jamming environments, especially when integrated with inertial sensors. The primary drawback is that all satellites are intimately related, and any error in one channel can potentially adversely affect other channels.

2.2 Centralized GPS/INS UTC with Vector Tracking

Vector tracking receiver processes the signal tracking and positioning by the filter together, and multiple channel signal tracking and motion model fusion filtering [4][5]. A Vector Delay/Frequency Lock Loop (VD/FLL) uses the filter to track the pseudo random noise (PRN) code phases and the carrier frequencies. The filter estimate all channels' pseudorange and pseudorange-rate according to receiver's navigation parameters and satellite ephemeris data, and the estimation information is sent to the local signal generator carrier and code NCO. In the cycle of each integrator and reset, the discriminator output of pseudorange and pseudorange-rate residual information is used to update the filter state[12,13].

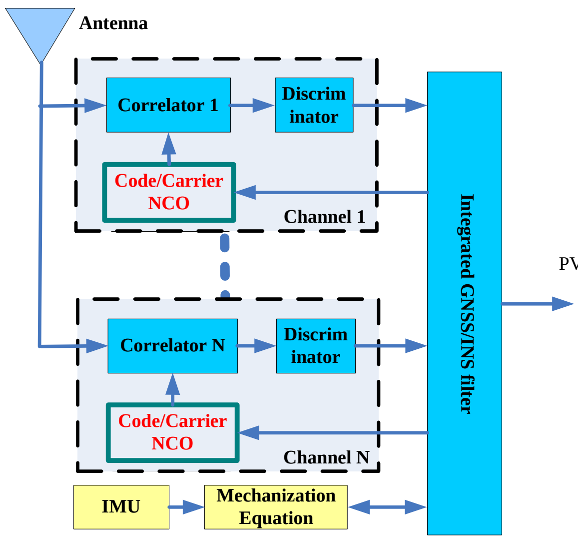

Fig.3 Vector-based GPS/INS UTC architecture

Extension of vector-tracking to UTC with an INS is possible by augmenting the architecture with an inertial measurement unit (IMU) and replacing the navigation filter with an integrated GPS/INS filter [3].The integrated filter output results such as positioning and velocity are equivalent to provide the reference movement trajectory for the GPS receiver. The essential is that using the INS subsystem and its integral algorithm replace the state forecasting process based on vector receiver state equation. Compared with vector receiver has the following advantages: the INS subsystem can grasp the receiver movement real time according to the sensing value, and the vector receiver even very reasonable motion model which cannot describe all the different movement model for the receiver, the architecture shown in Fig.3.

The system states are three position error components, the three velocity error components, three "platform" misalignment angles, three gyro drifts, three accelerometer zero bias of INS as well as clock bias and clock drift of GPS receiver, and the position and velocity error states are all in the ECEF frame[14].

$$X(t) = \begin{bmatrix} \delta P_{3\times1} & \delta V_{3\times1} & \varepsilon_{3\times1} & d_{3\times1} & b_{3\times1} & \delta t_{1\times1} & \delta f_{1\times1} \end{bmatrix}^T_{17\times1} \quad (1)$$

$$\dot{X}(t) = \begin{bmatrix} \delta\dot{P} \\ \delta\dot{V} \\ \dot{\varepsilon}^e \\ \dot{d} \\ \dot{b} \\ \delta\dot{t} \\ \delta\dot{f} \end{bmatrix} = \begin{bmatrix} \delta V^e \\ -F^e\varepsilon^e + N^e\delta r^e - 2\Omega_{ie}^e\delta V^e + R_b^e d \\ -\Omega_{ie}^e\varepsilon^e + R_b^e b \\ -Ad + W_d \\ -Bb + W_b \\ 0\cdot\delta t + \delta f + w_b \\ 0\cdot\delta f + w_d \end{bmatrix} \quad (2)$$
$$= F(t)X(t) + GW$$

We denoted as:

$$X^e(t) = F^e(t)X^e(t) + G^e W \quad (3)$$

The system noise section is

$$G^e W = (0 \quad \Delta g^e + R_b^e K f^b \quad 0 \quad W_d \quad W_b)^T \quad (4)$$

The dynamic matrix of the equation of state is a 17 order sparse matrix. The concrete structure is:

$$F(t) = \begin{bmatrix} 0_{3\times3} & I_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{2\times2} \\ N^e & -2\Omega_{ie}^e & -F^e & R_b^e & 0_{3\times3} & 0_{2\times2} \\ 0_{3\times3} & 0_{3\times3} & -\Omega_{ie}^e & 0_{3\times3} & R_b^e & 0_{2\times2} \\ 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & -A & 0_{3\times3} & 0_{2\times2} \\ 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & 0_{3\times3} & -B & C \\ 0_{2\times2} & 0_{2\times2} & 0_{2\times2} & 0_{2\times2} & 0_{2\times2} & 0_{2\times2} \end{bmatrix}_{17\times17} \quad (5)$$

where

$$GW = \left(0 \quad \Delta g^e + R_b^e K f^b \quad 0 \quad W_d \quad W_b \quad w_b \quad w_d\right)^T \quad (6)$$

Ω_{ie}^e is anti-symmetric matrix of the earth angular velocity w_e.

F^e is anti-symmetric matrix of the specific force f^e.

$$N^e = \frac{kM}{r^3}\begin{bmatrix} -1+\frac{3x^2}{r^2} & \frac{3xy}{r^2} & \frac{3xz}{r^2} \\ \frac{3xy}{r^2} & -1+\frac{3y^2}{r^2} & \frac{3yz}{r^2} \\ \frac{3xz}{r^2} & \frac{3yz}{r^2} & -1+\frac{3z^2}{r^2} \end{bmatrix} + \begin{bmatrix} w_e^2 & 0 & 0 \\ 0 & w_e^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (7)$$

kM is the product of gravitational constant and the earth mass; $P^e = \begin{pmatrix} x & y & z \end{pmatrix}$ is carrier position coordinate on geographic coordinate system.

the R_b^e matrix is referred to as the direction cosine matrix from the body frame to the navigation frame.

Through laboratory and field testing instrument, can obtain gyro constant drift and accelerometer constant bias term, and correct the corresponding measurements (specific force and angular velocity). However, the residual error still exists, which can be considered as a stochastic process, which is represented by a stochastic model. Here using d and b two vector respectively, the gyro drift and accelerometer bias of the random component. And that is often expressed as colored noise, first-order Markov process.

where $A = diag(\alpha_i)$ and $B = diag(\beta_i)$ are diagonal matrix, the element is equal to the inverse correlation time of the corresponding stochastic process.

The filter state is updated by the discriminator output of all channels. The output of the code discriminator is converted into pseudorange residuals, the carrier frequency discriminator output is converted to pseudorange-rate residuals, the measurement equation are:

$$Z(t) = H(t)X + v(t) \quad (8)$$

where

$$H(t) = \begin{bmatrix} a_{x,1} & a_{y,1} & a_{z,1} & 0_{1\times3} & 0_{1\times9} & 1 & 0 \\ 0_{1\times3} & a_{x,1} & a_{y,1} & a_{z,1} & 0_{1\times9} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{x,N} & a_{y,N} & a_{z,N} & 0_{1\times3} & 0_{1\times9} & 1 & 0 \\ 0_{1\times3} & a_{x,N} & a_{y,N} & a_{z,N} & 0_{1\times9} & 0 & 1 \end{bmatrix}_{2N\times2N}$$

$$Z(t) = [\delta\rho_1 \quad \delta\dot{\rho}_1 \quad \cdots \quad \delta\rho_N \quad \delta\dot{\rho}_N]^T$$

In this formula the variables $a_{x,N}, a_{y,N}, a_{z,N}$ are the components of the line-of-sight unit vector from the user to the N-th satellite.

The discretization of the system state equation and measurement equation are:

$$\begin{cases} X(k) = \Phi(k \mid k-1)X(k-1) + W(k-1) \\ Z(k) = H(k)X(k) + V(k) \end{cases} \tag{9}$$

The value of the filter is discretized according to the filtering equation; we do not repeat them here.

3 The effect of positioning error when measurements have faults

The mechanism of fault generating is introduced in this section firstly, and then analysis the measurement fault on the impact of positioning error from the theoretical.

3.1 Fault mechanism

Individual inertial sensor faults are due to hardware failure and can manifest as no outputs at all, null readings, repeated readings, or simply much larger errors than specified. Once a sensor fault has been detected, no further data from that sensor should be accepted. Unless there are redundant inertial sensors, this means discarding the whole inertial navigation solution. Large errors exhibited by all the inertial sensors can be an indication of a much-higher vibration environment than the system is designed for or of a mounting failure. The whole IMU or INS may also exhibit a power failure, software failure, or communications failure, in which case a reset should be attempted. So this paper mainly considers the GPS faul[15]t.

GPS fault modes may be divided into four categories: satellite faults; unusual atmospheric propagation; local channel failures, which comprise faults affecting individual channels of a single set of user equipment; and general user equipment faults. A summary may be found in [10].In this paper, we only focus on local channel failures to research.

Other causes of local channel failures are multipath, tracking loops in the process of losing lock, and receiver hardware and software faults affecting individual channels. Satellite faults and wide-area atmospheric problems may be detected as local channel failures where no monitoring network is used or to provide a backup to a network. FDI and FDE level protection against single-channel failures can usually be obtained provided sufficient satellites are tracked. The faulty signal is simply discarded and a navigation solution computed using the remaining signals.

The fault was mentioned in this paper refers to the measurement of discriminator output have bias. Most of the literatures generally considered the VD/FLL tracking are unbiased, but in the fact the VD/FLL algorithm will be introduced to the bias [11], even in GPS/INS UTC algorithm, the INS estimated only to the acceleration and cannot be estimated higher order acceleration derivative, which will result VD/FLL discriminator output bias because the carrier complex dynamic appears. Variety of factors will lead to the measurement bias such as the diffuse reflection multipath effects, atmospheric delay model imprecise and so on in the real condition, which impact on the positioning measurement accuracy.

3.2 The theoretical analysis on positioning error when measurements have faults

In order to simplify the theory analysis of positioning error, we made two assumptions on the measurement error model:

(1) The measurement errors of pseudorange residuals are the same normal distribution and the mean are all 0 and variances are σ_ρ^2 when the channel has no fault.

(2) Different channels measurement errors are unrelated, so the covariance of measurement errors vector $V(k)$ is a diagonal matrix.

Assuming at time k, only channel j has fault in all tracking channels because complex dynamics or multipath, consider the following channel j model with fault:

$$Z_j(k) = Z_{jr}(k) + Z_{jf}(k) \tag{10}$$

Where $Z_{jr}(k) = H_j(k)X_j(k) + V_j(k)$ is the normal measurement, and the covariance of the measurement noise $V_j(k)$ is σ_ρ^2, $Z_{jf}(k) = f_j^{k,s}\mu_j(k)$ is the fault measurement information, and $\mu_j(k)$ is a random vector, which represents the fault value, $f_j^{k,s}$ is a piecewise function,

$$f_j^{k,s} = \begin{cases} 1, & [k,s] \\ 0, & [0,(k-1)] \bigcup [(s+1),+\infty) \end{cases} \tag{11}$$

The filter updated state at time k and its covariance are

$$\hat{X}_j(k) = \hat{X}_{jr}(k) + \hat{X}_{jf}(k) \tag{12}$$

$$\begin{aligned} P(k) = &\left[I - K(k)H(k)\right]P(k \mid k-1)\left[I - K(k)H(k)\right]^T \\ &+ K(k)R(k)K(k)^T \end{aligned} \tag{13}$$

where $\hat{X}_{jr}(k)$ is the normal measurement filtering state, and $\hat{X}_{jf}(k)$ indicates the filtering state error caused by fault measurement, their values were:

$$\begin{aligned} \hat{X}_{jr}(k) = &P(k)[P^{-1}(k \mid k-1)\hat{X}_j(k \mid k-1)] \\ &+ P(k)[H^T(k)R^{-1}(k)Z_{jr}(k)] \end{aligned} \tag{14}$$

$$\hat{X}_{jf}(k) = P(k)H^T(k)R^{-1}(k)Z_{jf}(k) \quad (15)$$

Under normal conditions, the kalman filtering equation correct the state value by (14) equation. After correction positioning errors obey normal distribution with zero mean value and the variance is $P(k)$ .when channels have fault, positioning will lead to bias, the bias are determined by (15), the magnitude of bias are relate with the measurement value and satellites geometry distribution. The positioning errors are no longer zero mean, when channels have fault.

4 The Architecture and Algorithm Design of Ultra-Tightly Coupled GPS/INS Integration Based on Vector

The satellite signals are inevitable existence errors in the generation, transmission, processing. Thus the demand on fault tolerance of ultra-tightly coupled GPS/INS integration navigation system is growing higher and higher, which includes the ability of fault detection, isolation and system reconfiguration. We must adopt appropriate algorithm to improve the performance and make best use of the advantages and bypass the disadvantages. In this paper, we propose a fault-tolerant vector tracking filter algorithm and robust algorithm for Ultra-tightly coupled GPS/INS Integration using federated Kalman filter, was show the Fig 4.

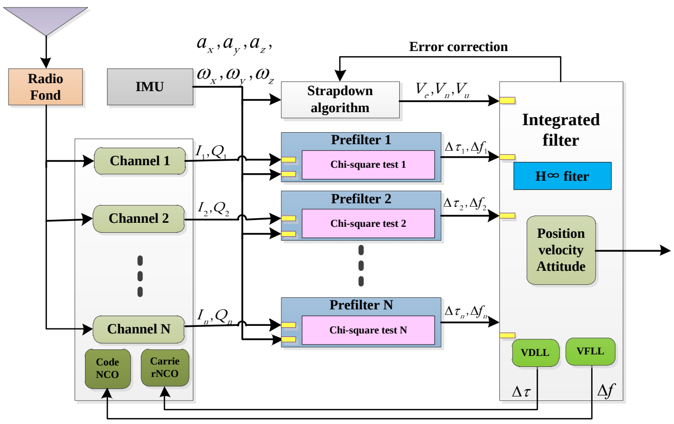

Fig.4 the Fault Detection Architecture and Robust filter of Ultra-Tightly Coupled GPS/INS Integration Based on Vector

In the architecture, through the use of a master filter and a plurality of parallel tracking filter (also called pre-filter)to realize the navigation function, which in each of the pre-filter in each period of filter selection residual test method, after 1s with innovation sequence detecting method to test, the residual detection method easy to detect abrupt faults, and innovation sequence detecting method of slowly varying fault detection has good detection effect, greatly reducing receiver channel fault effect on integrated navigation system of fusion results, guarantee system in fault can maintain a high accuracy. While the main filter using H- infinity(H ∞) robust filtering. GPS receiver for each channel with a pre-filter to achieve tracking, parallel tracking function, the filter can achieve the essence of the optimal tracking loop. All channels of the tracking filter output and SINS output to a integrated filter, and finally realize the information fusion and navigation and positioning algorithm, get the final navigation output. After the final solution of integrated filter to aid the receiver tracking loop, the architecture with high accuracy, high stability and strong fault tolerance and robustness.

On the one hand, the GPS signal is used to update the SINS, on the other hand, SINS and satellite ephemeris is also used to calculate vector with respect to the GPS pseudorange and pseudorange rate error. Because SINS has a high positioning accuracy and speed measurement accuracy in a certain range, using these information to track the GPS signal can greatly improve the positioning accuracy, dynamic performance and reliability of GPS. The precision of GPS information in turn can be improved by improving the precision of SINS, which makes the system more accurate than single system. The GPS receiver loop can effectively improve the equivalent bandwidth of the loop, improve the anti-interference ability of the receiver, reduce the error caused by the dynamic stress, and improve the tracking performance of the receiver.

4.1 Fault Detection base on KF innovations

The Kalman filter is a powerful tool for detecting faults.

The measurement innovations, $\gamma(k)$,of a Kalman filter, provide an indication of whether the measurements and state estimates are consistent. Innovation filtering may be used to detect large discrepancies immediately[12].

For a true Kalman filter, the measurement innovation vector is:

$$\gamma(k) = Z(k) - \hat{Z}(k|k-1) \quad (16)$$

The covariance of the innovations, $A(k)$, comprises the sum of the measurement noise covariance and the error covariance of the state estimates transformed into measurement space. Thus:

$$A(k) = H(k)P(k|k-1)H^T(k) + R(k) \quad (17)$$

which is the denominator of the Kalman gain.The normalized innovations are defined as:

$$y_k = \frac{\gamma(k)}{\sqrt{A(k)}} \quad (18)$$

4.2 H-infinity filter

Kalman filtering assumes that the message generating process has a known dynamics and that the exogenous inputs have known statistical properties. Unfortunately, these assumptions limit the utility of minimum variance estimators in situations where the message model and/or the noise descriptions are unknown[13].

We define the following cost function:

$$J_1 = \frac{\sum_{k=0}^{N-1} \|z_k - \hat{z}_k\|_{S_k}^2}{\|x_0 - \hat{x}_0\|_{P_0^{-1}}^2 + \sum_{k=0}^{N-1} (\|w_k\|_{Q_k^{-1}}^2 + \|v_k\|_{R_k^{-1}}^2)} < \frac{1}{\theta} \quad (19)$$

where P_0 , Q_k , R_k and S_k are symmetric, positive definite matrices chosen by the engineer based on the specific problem , and θ is our user-specified performance bound.

H-infinity filter algorithm process is on the follow：

$$\begin{aligned} \bar{S}_k &= L_k^T S_k L_k \\ K_k &= P_k [I - \theta \bar{S}_k P_k + H_k^T R_k^{-1} H_k P_k]^{-1} H_k^T R_k^{-1} \\ \hat{x}_{k+1} &= F_k \hat{x}_k + F_k K_k (y_k - H_k \hat{x}_k) \\ P_{k+1} &= F_k P_k [I - \theta \bar{S}_k P_k + H_k^T R_k^{-1} H_k P_k]^{-1} F_k^T + Q_k \end{aligned} \quad (20)$$

The following condition must hold at each time step K in order for the above estimator to be a solution to the problem:

$$P_k^{-1} - \theta \bar{S}_k + H_k^T R_k^{-1} H_k > 0 \quad (21)$$

5 Simulation Analyses

We mainly focus on the simulation and verification work in section 3 and 4.

5.1 Position effect when satellite channel fault

In the section 3, the performance of the navigation is analysed, and the analytic expression is obtained. This section will use simulation tools to further analyse and verify the previous conclusions.

In this paper, we only analyses the single-channel fault, multi-channel fault analysis is similar. The channel fault causes the positioning error have been analysed and derived analytic formula in section The effect of positioning error when measurements have faults. In this section we will quantitative verification of the positioning error by theoretical simulation. The simulation conditions of this paper: the user position in ECEF frame are (-2171918, 4385950, 4076294), medium accuracy IMU, integrated filter update time is 10ms, using the temperature compensated crystal oscillator (TCXO) type clock, number of satellites are 10 and 5 constellation respectively, The Dilution of Precision (DOP) values for the different satellites constellation are shown in Table 1, wherein the 5 constellation is selected from the 10 constellation channel 1,3,5,7 and 9.

Table 1 DOP values for different satellite configuration

Satellites Number	PDOP	HDOP	VDOP
10	1.6149	1.1986	1.0823
5	3.2675	2.3736	2.2456

In order to maintain VD/FLL tracking, the fault are d, d/2 and d/3 which were translated into pseudo ranges residuals, wherein the measurement noise of each channel is calculated by formula in reference [8] accord to CN0.where the symbol d is the correlator spacing of the early and prompt PRN replicas, expressed in fraction of a chip. A correlator spacing of one half chip is used for all the simulation results.

5.1.1 The impact on positioning error of single-channel fault on the same constellation

We performed simulation to analysis that only channel number 5 has fault, when all channels C/N0 change.

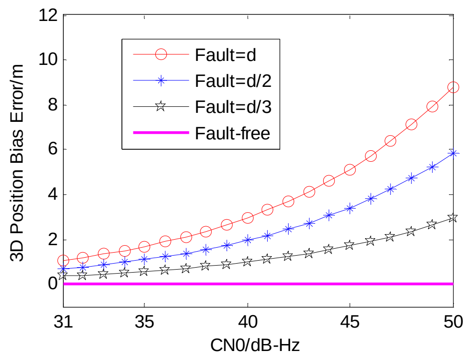

Fig.5 The channel 5 bias induce positioning bias when tracking 10 satellites on different C/N0

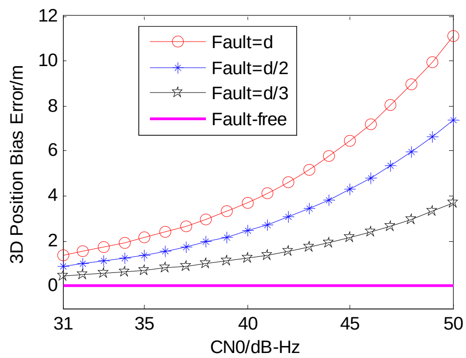

Fig.6 The channel 5 bias induce positioning bias when tracking 5 satellites on different C/N0

Fig.5 and Fig.6 are 10 constellations and 5 constellations simulation results respectively. The results show that the positioning bias becomes larger as the signal energy becomes larger under the same constellations distribution; the positioning bias are larger on 5 constellations than 10 constellations under the same C/N0, the positioning bias are related with DOP factor, the DOP factor are larger, the larger positioning bias. Therefore, it is particularly important for fault detection, when signal are strong and positioning satellites number are less.

5.1.2 The impact on positioning error when different single-channel faults on the same constellations

The signal C/N0 are 40dB-Hz all the time, we performed simulation to analysis when the different single-channel have fault on 10 constellations, was shown in Fig.7, the results show that different channels have different positioning bias, and the positioning bias is related to fault value and the unit vector between user and the satellite.

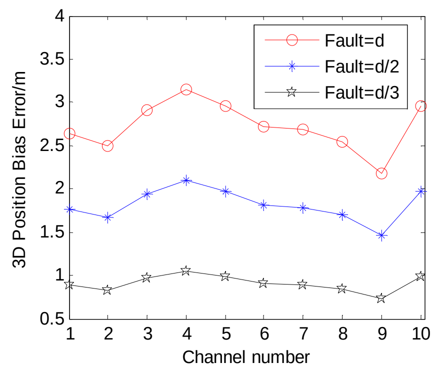

Fig.7 Different channels observation bias induce positioning bias when tracking 10 satellites

Table 2 Different channels observation bias d induce positioning when tracking 5 and 10 satellites

Num \ Channel	1	2	3	4	5
10	2.65	2.91	2.95	2.68	2.19
5	4.03	4.60	3.71	3.35	4.01

Table 2 is positioning bias when tracking 5 and 10 satellites on the same single -channel fault, the results show that: in the same channel fault the 5 constellation positioning bias are larger than the 10 constellation, the positioning bias have relation with DOP factor, the DOP factor is larger, the greater the positioning bias.

5.1.3 Simulation results of multi-channel fault resulting in positioning bias

We simulation that multi-channels have fault at the same time on 10 constellation distribution.Fault number N denote the fault channel number $1,\ldots N$,respectively. The experimental results show that, along with the fault channel increase the position bias becomes large. And the signal energy is stronger, the greater the positioning bias was shown in Fig.8.

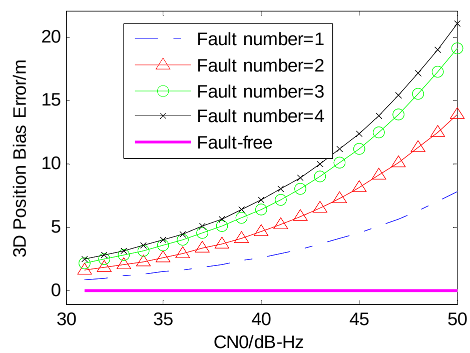

Fig.8 The multichannel bias induce positioning bias when tracking 10 satellites on different C/N0

5.1.4 The positioning accuracy simulation on remove fault channel or not

With the change of the signal energy, we simulation the positioning accuracy, and channel 5 still has fault. Fig.9 shows the result of different constellations distribution, whether removal of the fault channel or not, there is almost no effect on the positioning accuracy, but the geometric distribution have a greater impact on the positioning accuracy.

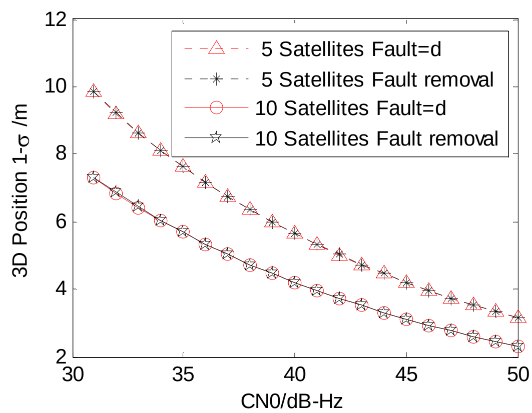

Fig.9 Fault removal and presence of channel 5 induce positioning error when tracking 10 and 5 satellites on different C/N0

5.2 Simulation on the architecture Vector-Based UTC GPS/INS Integration

5.2.1 Simulation system design and data generation

IMU data and GPS intermediate frequency (IF) data were generated by simulation test. Since the computational requirements of the software receiver are so stringent, only 125-s data are considered here。

The vehicle turn north linear motion and the trajectory covered static periods, accelerations, decelerations, jerks and uniform velocity with the following settings. The vehicle original position is on N:5.0°, E:5.0°, Alt:5m. Vehicle is stationary during time period from 0s to 35s.During time period of from 35s to 45s, from 55s to 75s, from 77s to 92s and from 102s to 112s, Vehicle is uniform jerks motion, and the uniform jerks(m/s^3) are 10,-20,20,10 separately. During time period of from 45s to 55s, from 70s to 77s and from 92s to 102s, Vehicle is uniform acceleration motion, and the uniform acceleration (m/s^2) is 100,-200 and 100 separately. The vehicle is uniform velocity motion during time period from 112s to 125s.

The motions of a vehicle are generated by above trajectory. The generation of simulated signals of inertial sensors is an inverse process of INS navigation mechanization. Given that all the INSs 125s only without alignment errors and the only inertial sensor error source of each INS is the gyro bias, e.g. in run bias of 0.1deg/h, precision IMU in this paper.

We consider tracking of the GPS L1 carrier frequency in this work. The IF data are obtained by YUMA almanac reduction which obtain from the website of U.S Navigation Center. The GPS simulator time is July 3, 2006,12:00:28. The sampling frequency is 12MHz, and the IF is 3.563MHz.The GPS satellite sky plot during vehicle test is shown Fig.10. Fig.11 shows corresponding line of sight (LOS) Doppler between PRN10 and receiver.

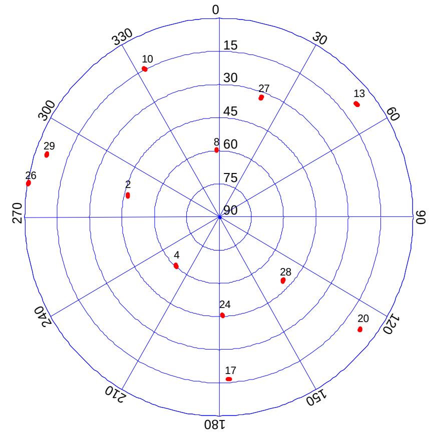

Fig.10 GPS satellite sky plot during vehicle test

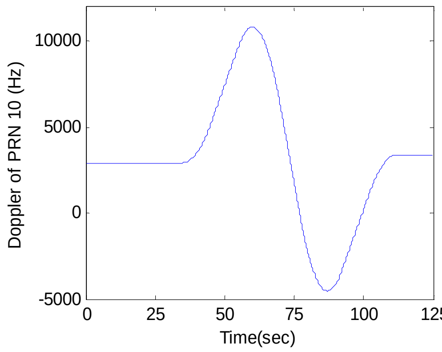

Fig.11 LOS Doppler between PRN10 and receiver

5.2.2 Simulation result analyses

In order to facilitate the comparison and analysis, this section were in the colored noise is existent conditions with H-infinity filtering and extended Kalman filtering results were compared, because the direction of X and Y direction positioning and velocity error curve is similar, so this article only gives in X direction and Z direction combination filter were used H-infinity and EKF filtering error curve, as shown in Fig.12- Fig.15.

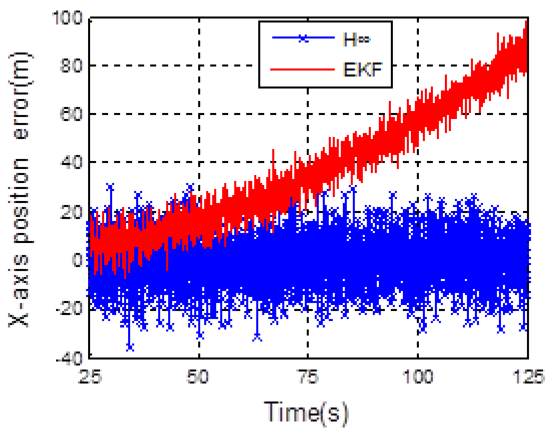

Fig.12 X-axis Position errors comparison EKF to H∞ algorithms during colored noise

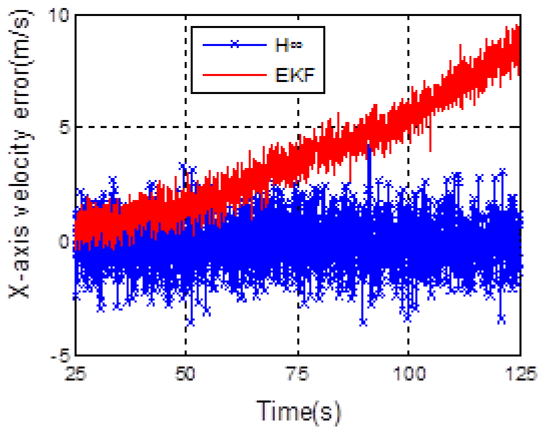

Fig.13 X-axis velocity errors comparison EKF to H∞ algorithms during colored noise

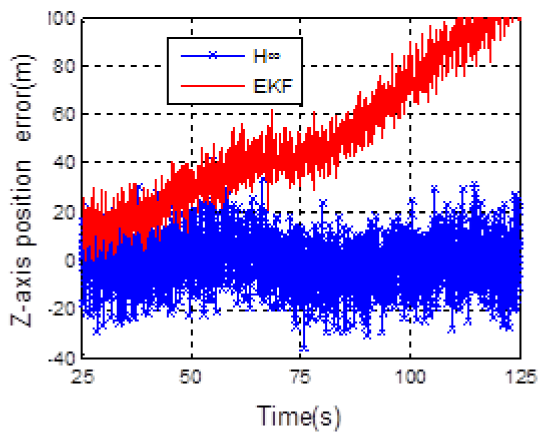

Fig.14 Z-axis Position errors comparison EKF to H∞ algorithms during colored noise

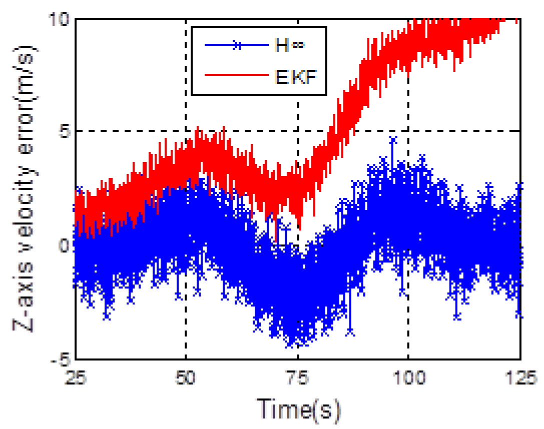

Fig.15 Z-axis velocity errors comparison EKF to H∞ algorithms during colored noise

EKF with positioning and velocity measuring the divergence time growth, cannot work normally, and H-infinity filter is reliable, but the position and velocity accuracy is slightly worse. This is illustrated with the EKF filtering compared and H-infinity filter has very strong robustness, even if the input signal with constant drift and random, filters convergence.

Due to the current GPS if analogy simulation cannot get the data of the fault channel, so this paper has no simulation for fault tolerance, the next will carry out research and verification for fault tolerance.

6 Conclusions

In this paper, we first explain the structure of based vector tracking GPS/INS UTC system, and illustrate the fault mechanism, then analyse the UTC system positioning error in detail when measurements have fault and finally through the simulation experiments quantitative analysis, at the last we design a fault detection architecture and robust filter of UTC GPS/INS integration. The results show that: (1) when the measurements have fault, the positioning results will appear bias, and measurements bias are greater, the greater the positioning bias; (2) when different satellite channel appears the same fault, the different effects on the positioning bias in the same constellation , depending on the line of sight relevant between the satellite and the user; (3) the same channel fault is different in the different constellations, and have related with the satellite geometry distribution, the geometry distribution are better the smaller the error; (4) the stronger the signal energy, the channel fault have greater impact on positioning bias. (5) The application of H-infinity filtering technology is effective on the GPS/INS navigation system with colored noise.
(6) Using H-infinity filtering technique of GPS/INS UTC system filtering, the state equation of the system don't need of gyro and acceleration error modelling and estimation, thereby reducing the dimensionality of the state variables of the system, reduce the amount of computation, can improve the filtering speed, is conducive to the real time implementation of integrated navigation system. In practical applications, a lot of factors can lead to measurements fault, but we cannot distinguish the reason. In order to reduce the fault satellite channel effect on overall system performance, next we will further verification the fault tolerant and H-infinity robust filter algorithm.

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Reference

[1]P.Ward,J.W.Betz,andC.J.Hegarty, *Understanding GPS: Principles and Applications*, Artech House Publishers, 2006.

[2]Stefan Kiesel, Markus Langer, Gert F, Trommer. Real Time Implementation of a Non-Coherent Deeply Coupled GPS/INS System. *Proceedings of the 2014 International Technical Meeting of The Institute of Navigation*, San Diego CA, 2014.pp.12-21.

[3]Matthew Lashley, David M.Bevly, John Y.Hung. Analysis of Deeply Integrated and tightly coupled architectures, *IEEE/ION Position Location and Navigation Symposium*. California,2015.pp.382-396.

[4]D. Benson. Interference benefits of a vector delay lock loop (VDLL) GPS receiver, *Proceedings of Annual Meeting of the Institute of Navigation* ,2013,pp.749-756.

[5]Nazia Kanwal, Vector tracking loop design for degraded signal Environment.,*Tampere University of technology*,2011.

[6] Kennedy, S. and Rossi, J. Performance of a deeply coupled commercial grade GPS/INS system from KVH and NovAtel Inc. *In Proceedings of IEEE/ION Position Location and Navigation Symposium Conference*,Monterey, CA, 2008,pp.17-24.

[7]Matthew Lashley, David M and John Y. Performance Analysis of Vector Tracking Algorithms for Weak GPS Signal in High Dynamic. *IEEE Journal Of Selected In Signal Procession*, 2012,3(2).pp.661-673.

[8]Matthew Lashley. Modelling and Performance Analysis of GPS Vector Tracking Algorithms, *Auburn University*,2009.

[9]Dong Xurong,Zhang Shouxin,Hua Zhongchun. GPS/INS integrated navigation positioning and application. *National University of Defense Technology Press.* 1998.

[10] Bhatti, U. I., and W. Y. Ochieng, Failure Modes and Models for Integrated GPS/INS Systems, *Journal of Navigation*, Vol.60,No.2,2007, pp.327–348.

[11]Xiao Zhibing,Tang Xiaomei,Pang Jing,Wang Xuefei. The study of code tracking bias in vector delay lock loop. *Scientia Sinica Phys,Mech & Astron,* Vol .40,No.10,2013,.pp.568-574.

[12] Cimpoesu EM, Ciubotaru BD, Stefanoiu D. Fault Detection and Diagnosis Using Parameter Estimation with Recursive Least Squares, *Control Systems and Computer Science (CSCS), 2013 19th International Conference* on: 18 – 23.

[13] Dan Simon. Optimal State Estimation: Kalman, H Infinity, and Nonlinear Approaches, *John Wiley & Sons,*2006.

[14]M.G. Petovello, C. O'Driscoll ,G. Lachapelle. Weak Signal Carrier Tracking Using Extended Coherent Integration with an Ultra-Tight GNSS/IMU Receiver, *European Navigation Conference*,2008.pp.1-11.

[15]Himan Zarza, Saleh Yousefi and Abderrahim Benslimane, RIALS: RSU/INS-aided localization system for GPS-challenged road segments,*Wireless Communications and Mobile Computing,*Vol. 16, NO. 10, 2016,pp 1290–1305.