WIFI AIDED INTEGRITY IMPROVEMENT IN MEMS INS/GNSS INTEGRATION

Liu Hua（刘华），*Liu Tong*（刘彤）

(School of Automation, Beijing Institute of Technology, 100081, P. R. China)

Abstract: The reliability of global navigation satellite system (GNSS) positioning degrades when satellite signals are interfered. Such degradation is hard to be deteced by a micro-electro mechanical system (MEMS) based inertial system(INS)/GNSS, integrating navigation system with a conventional Kalman filtering, which results in potential integrity problem of the system. Hence, an algorithm combining wireless fidelity (WiFi) signal with a federated Kalman filter (FKF) is proposed to identify the system integrity in dense urban navigation. The criterion of the system integrity detection is created followed by the derivation of the integrity coefficient. The field test shows that integrity changes can be captured by applying WiFi, and the maximum positioning error is reduced by 67% without compensation of inertial sensors in integrity deterioration.

Key words: MEMS INS; integrated navigation; WiFi; FKF

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INTRODUCTION

Micro-electro mechanical system based inertial system (MEMS INS) using MEMS inertial sensors inherits the outstanding features of the conventional INS, i. e., small size, light weight, low power, long life cycle, high reliability, and affordable cost. Unfortunately, due to the immaturity of current manufacturing techniques of sensor, the unexpected fast error propagation prevents MEMS INS from being one of comfortably autonomous navigation systems with long term accuracy[1-2]. The coupling of global navigation satellite system (GNSS) and INS overcomes each of their limitations[2]. Wireless fidelity (WiFi) has been gradually employed by vehicle positioning technologies[3]. Far beyond an auxiliary positioning source, WiFi is herein used to improve the integrity of MEMS INS/GNSS integrated system when the vehicle travels in urban canyon environment with severe multipath.

1 FEDERATED KALMAN FILTER IN WIFI/MEMS INS/GNSS INTEGRATED SYSTEM

1.1 Overview

A WiFi pair consists of an access point(AP) and a signal receiver, neither of which is exclusive to the other. WiFi presents positioning capability indirectly by means of its AP media access control (MAC) address information rather than the time of arrival (TOA) technique which is typically used in the cell phone positioning. Its receiver module is able to distinguish the signal quality based on the received signal strength indicator (RSSI), a measurement of the power present. The geodetic coordinates of AP and RSSI of wireless signal are generally broadcasted by its radio signal. The accuracy of WiFi positioning is around 30 m in circular error probability (CEP)[4]. The WiFi signal centers at 2.4 GHz without interference with GNSS signals and its strength ranges from −50 dBm to −90 dBm which is much stronger than GNSS signals. Although the

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Corresponding author: Liu Hua, Lecturer, E-mail: sogoliu@163.com.

WiFi signal is discontinuously available, approximately 30% in an urban with well established infrastructure[3], it can be used in the integrity monitoring and improvement for the GNSS and INS coupled system thanks to its stronger signal compared with that of GNSS.

1.2 Federated Kalman filter in integrated system

Kalman filter is one of the most effective estimation techniques to INS/GNSS integration. The extended Kalman filter (EKF) is a sequential recursive algorithm which can be divided into two loops, prediction loop and update loop. Federated Kalman filter (FKF) is typically considered as a mathematical transformation of EKF[5-7].

FKF allocates measurements from different sources into different local filters. The local filters run independently to isolate any subsystem failure, whose scheme enhances the system reliability. Local filters work in parallel and the master filter finally combines the outputs.

As far INS/GNSS with WiFi aiding as concerned, the system scheme based on FKF is diagrammed in Fig. 1. The EKF algorithm is used in each local filter.

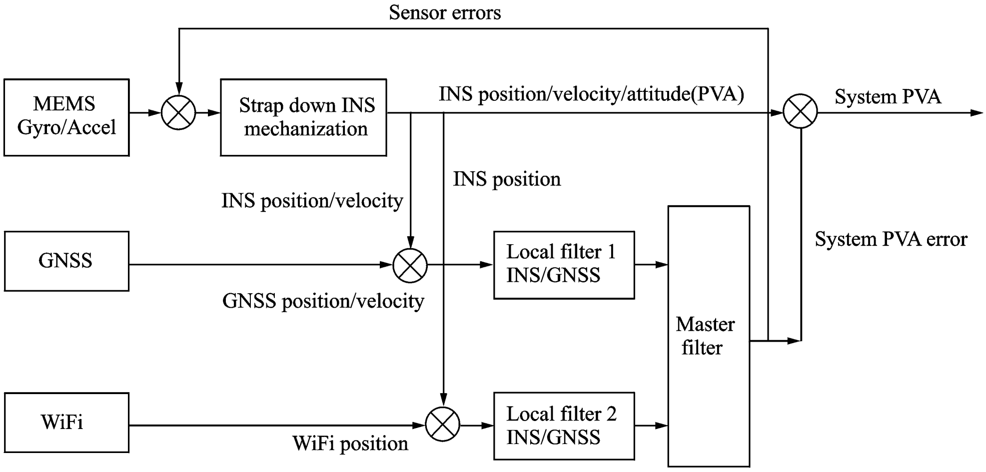


Fig. 1 WiFi aided GNSS/INS integration scheme

In FKF, the estimate $\hat{\boldsymbol{X}}_f(k)$ and its uncertainty $\boldsymbol{P}_f(k)$ of whole system can be written as

$$\boldsymbol{P}_f^{-1}(k)=\boldsymbol{P}_1^{-1}(k)+\boldsymbol{P}_2^{-1}(k) \tag{1}$$

$$\boldsymbol{P}_f^{-1}(k)\cdot\hat{\boldsymbol{X}}_f(k)=\boldsymbol{P}_1^{-1}(k)\cdot\hat{\boldsymbol{X}}_1(k)+\boldsymbol{P}_2^{-1}(k)\cdot\hat{\boldsymbol{X}}_2(k) \tag{2}$$

where $\hat{\boldsymbol{X}}_1(k)$ and $\hat{\boldsymbol{X}}_2(k)$ are the estimates of subsystems at the kth epoch, respectively, $\boldsymbol{P}_1(k)$ and $\boldsymbol{P}_2(k)$ the uncertainty of $\hat{\boldsymbol{X}}_1(k)$ and $\hat{\boldsymbol{X}}_2(k)$, respectively. For the local filter 2, its fusion error from EKF is determined by both INS error and observed WiFi signal quality which is associated to RSSI.

1.3 System dynamic equation

The error of navigation system $\boldsymbol{X}$ is selected as the state to be estimated and its dynamic equation can be written as

$$\boldsymbol{X}_{k+1}=\boldsymbol{\Phi}_{k+1/k}\boldsymbol{X}_k+\boldsymbol{w}_k \quad k=1,2,\cdots,N \tag{3}$$

where $\boldsymbol{\Phi}_{k+1/k}$ refers to the INS transition matrix from the kth epoch to the $(k+1)$th epoch and is determined by the INS basic mechanization equation[2], $\boldsymbol{w}_k$ the system response to the driving white noise during the interval from k to $k+1$ with an assumption of zero-mean and Gaussian distribution. Either local filter described in Fig. 1 uses a 15-state vector consisting of errors as follows

$$\boldsymbol{X}_1=\boldsymbol{X}_2=[\delta P_{\mathrm{E}} \quad \delta P_{\mathrm{N}} \quad \delta P_{\mathrm{U}} \quad \delta V_{\mathrm{E}} \quad \delta V_{\mathrm{N}} \quad \delta V_{\mathrm{U}} \quad \delta A_{\mathrm{p}} \quad \delta A_{\mathrm{r}} \quad \delta A_{\mathrm{h}} \quad gb_x \quad gb_y \quad gb_z \quad ab_x \quad ab_y \quad ab_z]^{\mathrm{T}} \tag{4}$$

where $[\delta P_{\mathrm{E}} \quad \delta P_{\mathrm{N}} \quad \delta P_{\mathrm{U}}]^{\mathrm{T}}$ refers to the positioning error in the east-north-up (ENU) frame, the east definition coincides with the direction of the Earth auto-rotation; $[\delta V_{\mathrm{E}} \ \delta V_{\mathrm{N}} \ \delta V_{\mathrm{U}}]^{\mathrm{T}}$ refers to velocity error in ENU frame; $[\delta A_{\mathrm{p}} \ \delta A_{\mathrm{r}} \ \delta A_{\mathrm{h}}]^{\mathrm{T}}$ refers to the pitch, roll and heading angle errors, respectively, via a definition of positive heading from north to east; $[gb_x \ \ gb_y \ \ gb_z]^{\mathrm{T}}$ refers to the stochastic part biases of gyros along three axes of the body frame defined as right-forward-vertical, and each axis bias is described by a first-order Gauss-Markov model; $[ab_x \ \ ab_y \ \ ab_z]^{\mathrm{T}}$ is similar to that of gyros and refers to stochastic part bias of accelerometers in the body.

1.4 Measurement equation

The system measurement equation is described as follows

$$\boldsymbol{Z}_{k+1} = \boldsymbol{H}_{k+1}\boldsymbol{X}_{k+1} + \boldsymbol{n}_{k+1} \qquad k=1,2,\cdots,N \tag{5}$$

where $\boldsymbol{Z}_{k+1}$ is the system measurement with a measurement noise of $\boldsymbol{n}_{k+1}$, $\boldsymbol{H}$ the design matrix connecting $\boldsymbol{Z}$ and $\boldsymbol{X}$.

For the local filter 1, the position and velocity differences between INS and GNSS are considered as the subsystem measurements. Therefore, $\boldsymbol{Z}_{1,k+1}$ can be given as

$$\boldsymbol{Z}_{1,k+1} = [\boldsymbol{Z}_{\mathrm{P,ENU}} \quad \boldsymbol{Z}_{\mathrm{V,ENU}}]^{\mathrm{T}} = \boldsymbol{H}_{1,k+1}[\delta P_{\mathrm{E}} \quad \delta P_{\mathrm{N}} \quad \delta P_{\mathrm{U}} \quad \delta V_{\mathrm{E}} \quad \delta V_{\mathrm{N}} \quad \delta V_{\mathrm{U}}]^{\mathrm{T}} \tag{6}$$

The design matrix $\boldsymbol{H}$ is given as

$$\boldsymbol{H}_{1,k+1} = \begin{bmatrix} \boldsymbol{I}_{3\times3} & \boldsymbol{0}_{3\times3} & \boldsymbol{0}_{3\times9} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{I}_{3\times3} & \boldsymbol{0}_{3\times9} \end{bmatrix} \tag{7}$$

For the local filter 2, horizontal position errors between WiFi and INS are considered as the subsystem measurements. Suppose that total of m WiFi APs are received at the $(k+1)$th epoch, so $\boldsymbol{Z}_{2,k+1}$ can be given as the following vector

$$\boldsymbol{Z}_{2,k+1} = [\boldsymbol{Z}_1 \quad \cdots \quad \boldsymbol{Z}_m]^{\mathrm{T}} = \boldsymbol{H}_{2,k+1}[\delta P_{\mathrm{E}} \quad \delta P_{\mathrm{N}}]^{\mathrm{T}} \tag{8}$$

Then, the design matrix of the local filter 2 is given as

$$\boldsymbol{H}_{2,k+1} = [\boldsymbol{I}_{m\times2} \quad \boldsymbol{0}_{m\times1} \quad \boldsymbol{0}_{m\times3} \quad \boldsymbol{0}_{m\times9}] \tag{9}$$

2 INTEGRITY OF INTEGRATION SYSTEM

2.1 Integrity of system

Integrity of a navigation system includes the ability to provide warnings when its result provides misleading data that can potentially create hazards[8]. In an obstructed environment, such as the dense urban canyon, the GNSS navigation accuracy degrades dramatically due to severe multipath, which results in the risk of misleading position and velocity information from the integrated system. Furthermore, the error of inertial sensors presented in Eq. (3) as part of estimates is scheduled to be feed backed and compensated. Meanwhile, the sensor outputs would be over adjusted once the system loses its integrity, which would eventually navigate in misleading attitude information as well.

2.2 Criterion of integrity monitoring by WiFi

It is normal that there exist large changes of position error, velocity error and attitude error at any two adjacent epochs. However, theoretically, the sensor error is supposed to change slowly. As long as the system satisfies the requirement of integrity, the difference of estimated inertial sensor errors between two local filters shown in Fig. 1 should be close to each other. The criterion of integrity monitoring can be thence set up as

$$J = \max\{\mathrm{Cov}(\hat{\boldsymbol{X}}_{1,m}) - \eta\mathrm{Cov}(\hat{\boldsymbol{X}}_{2,m})\} < \xi \tag{10}$$

where ξ is any given positive real number, m the mth column elements in $\boldsymbol{X}_1$ or $\boldsymbol{X}_2$, and $m=10,11,\cdots,15$ corresponding to the gyro bias errors and accelerometer errors in the state, respectively, η can be determined by the Gaussian Function *erf* in mathematics, $\mathrm{Cov}(\hat{\boldsymbol{X}}_{2,m})$ coming from the local filter 2 is actually the sensor error deviation apart from the estimate to the true value. Meanwhile, $\hat{\boldsymbol{X}}_{1,m}$ from the local filter 1 should be infinitely close to $\hat{\boldsymbol{X}}_{2,m}$ from the local filter 2 if both GNSS and WiFi are error-free. Taking $\hat{\boldsymbol{X}}_{2,m}$ as an approximate reference value, the probability of $\hat{\boldsymbol{X}}_{1,m}$ locating outside the confidence interval of $[\hat{\boldsymbol{X}}_{2,m} - \eta\mathrm{Cov}(\hat{\boldsymbol{X}}_{2,m})\eta\hat{\boldsymbol{X}}_{2,m} + \eta\mathrm{Cov}(\hat{\boldsymbol{X}}_{2,m})]$ is denoted by $(1-erf(\eta))$. Here η is selected as 6 to cover a typical value of mean time between failure (MTBF) about 5 000 h for the whole life of system. $1-erf(\eta=6)$ approximately gives a probability of 150 million[9] which indicates that an integrity alarm will never happen as long as the local filter 1 operates without deficiencies, always with reasonable measurement updates.

Finally, Eq. (10) can be re-written and normalized to define an integrity coefficient β as follows

$$\beta = \max\left\{\frac{E(\hat{\boldsymbol{X}}_{1,m} - \hat{\boldsymbol{X}}_{2,m})}{6 \times \mathrm{Cov}(\hat{\boldsymbol{X}}_{2,m})}\right\} \tag{11}$$

where $E(\cdot)$ is the operator of mathematical expectation. Obviously, the system integrity will be broken when $\beta > 1$. In the scenario of severe multipath, the integrity coefficient β is introduced to trigger rejections of the estimates from the MEMS INS/GNSS filter.

3 RESULTS AND ANALYSIS

The integrated system of MEMS INS/GNSS with WiFi aiding is conducted for a field test. The calibrated gyroscope and accelerometer bias instabilities are about 70 (°)/h and 25 mg, respectively. To evaluate the system performance with the proposed algorithm, a high grade INS built with laser optical gyros is operated at the same time as a reference system.

In order to verity the effectiveness of the integrity algorithm, a GNSS heavy degradation over 30 s is simulated offline to enlarge the actual multipath scenario from an average level to a severe level. The GNSS navigation data are added noise with a distribution of 30 m ± 30 m(1σ) and 0.5 m/s ± 2 m/s(1σ) on the positioning and velocity, respectively.

Fig. 2 compares the sensor error estimates from two local filters. It is obvious that the corresponding values have a big difference when GNSS navigation becomes worse dramatically due to the severe multipath.

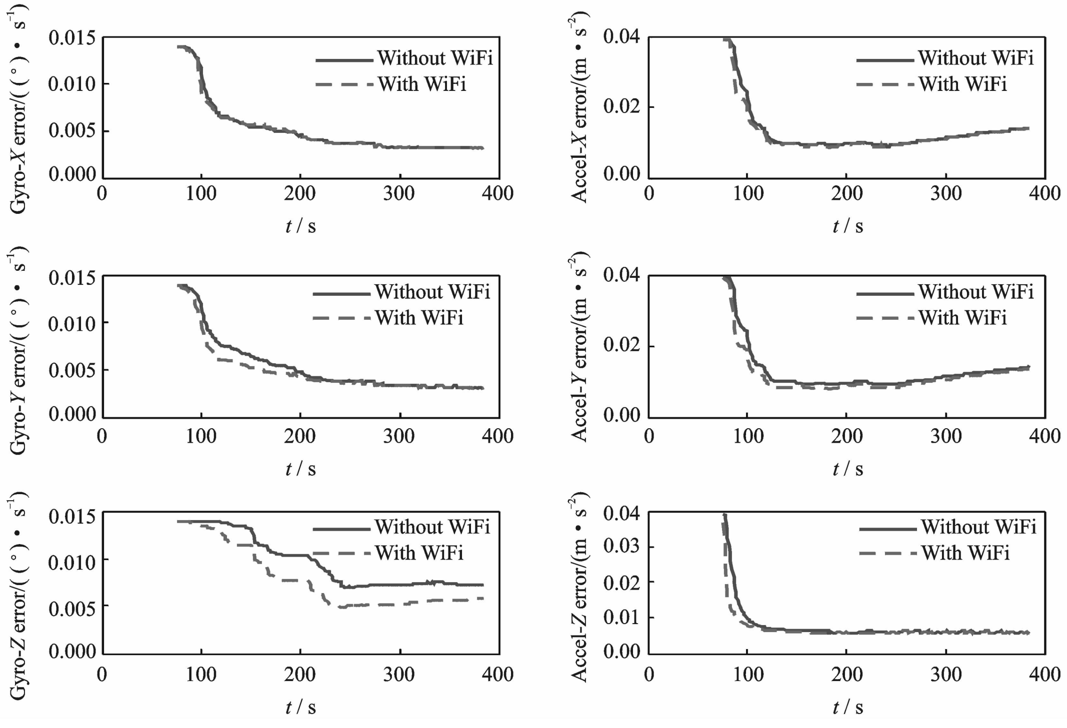


Fig. 2 Comparison of sensor errors from local filters

WiFi enabled local filter 2 is taken as the monitoring reference. From Fig. 2, the distinguish difference between filters indicates the misleading navigation data in the local filter 1. That is to say, the MEMS INS/GNSS integrated system probably does not possess integrity over some periods. To further detect the system integrity, the coefficient β should be calculated. Fig. 3 shows value changes of β。

From Fig. 3, the system can assert violation of integrity at coordinated universal time (UTC) [6 h 43 min 42 s + 100 s, 6 h 43 min 42 s + 125 s]. Therefore, the feedback of navigation error estimates and sensor error estimates should be rejected at the corresponding periods to keep the system integrity.

Fig. 4 shows horizontal positioning results with a comparison of with/without WiFi aiding

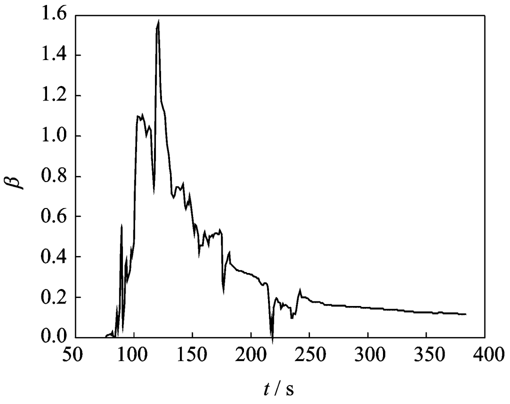
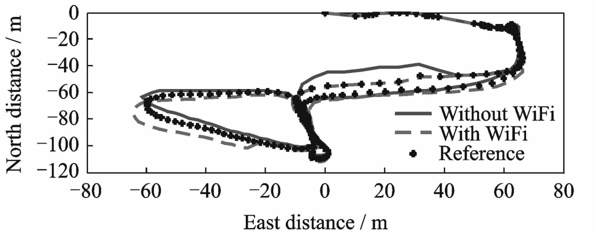
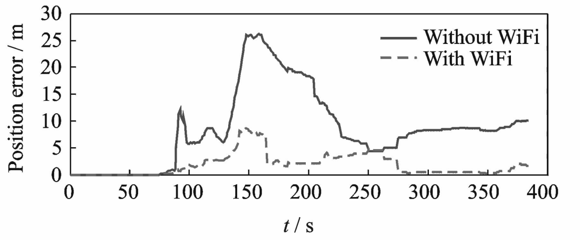


Fig. 3 Calculated value of integrity coefficient



(a) Comparison of trajectories



(b) Comparison of position error

Fig. 4 2D positioning result comparisons between algorithms with/without WiFi

integrity algorithm. The results show that the performance of MEMS INS/GNSS system is improved by use of the proposed integrity algorithm, in terms of maximum error reduction from 26.25 m to 8.64 m, i.e., 67% improvement.

4 CONCLUSION

For land vehicle navigation in the urban canyon with severe multipath environment, an integrity improvement algorithm for MEMS INS/GNSS integrated system with WiFi aiding is proposed. The FKF based system is designed and implemented following the creation of integrity detection criterion. The field test shows that the system integrity can be improved through rejecting unreliable inertial sensor compensations. The maximum positioning error is reduced by 67%.

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