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Research on GPS/INS/WIFI Personnel Tight Combination Positioning Method

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Abstract: With the development of current information technology, it has become a common demand to obtain accurate location information quickly. However, in the indoor environment where people generally live, GPS signals are partially occluded, and the INS of inertial navigation system will significantly increase the error due to the integral accumulation error. In view of the problems of poor robustness and low accuracy of the existing loose combination positioning methods, a GPS/INS/WIFI personnel tight combination positioning method was proposed by using the WIFI network signals with wide coverage at present. Firstly, the characteristics of WIFI positioning technology were analyzed, and the INS positioning error model was established. The measurement equation under tight coupling was established by using the pseudo range value of GPS and the RSSI parameters of WIFI system, and the state equation was established by using the INS error model, so as to realize the establishment of the combined GPS/INS/WIFI positioning state space equation. Then, based on unscented Kalman filter theory, a GPS/INS/WIFI based compact combined position solution model is established. Finally, the human wearable combined positioning experiment platform was used for experimental verification. The experimental results show that the GPS/INS/WIFI based tight combined positioning method can significantly adapt to the indoor environment with complex interference, has high positioning stability and positioning accuracy, and the maximum positioning error is 0.45m. Compared with the extended Kalman filter and Kalman filter, the positioning accuracy of unscented Kalman filter is improved by 56% and 89% respectively, which can meet the requirements of field use.

Keywords: Personnel combination positioning, GPS/INS/WIFI tightly integrated, Extended Kalman filter, Unscented Kalman filter, Positioning accuracy.

1. Quote

With the rapid development of information technology, all walks of life have more and more demands for moving target positioning technology, and for different application scenarios, a variety of supporting positioning systems have been developed, such as common GPS, Beidou and other satellite-based positioning systems [1], accelerometer, gyroscope and other positioning systems based on their own inertial information [2]. Ultra-wideband (UWB) [3], 4G communication [4], Zigbee[5], WIFI[6] and other local positioning systems based on short distance wireless communication technology. Therefore, according to the principle of obtaining position information, the current positioning technology can be divided into satellite technology, astronomy technology, inertial technology, geomagnetic technology, short distance wireless communication technology and so on. At present, GPS satellite navigation system is the most widely used in the world, which has been used on a large scale in the civil and military fields. However, GPS is susceptible to the influence of multi-path effect in the working process, so that the GPS is interfered, the signal-to-noise ratio is low, and the measurement error is increased. Especially in the urban, mountainous and other environments, part of the GPS satellite signals are easy to be blocked. As a result, the stability of measurement results is poor [7]. Therefore, in the high precision navigation system, only the use of GPS positioning system can not meet the needs of users. Inertial Navigation System (INS) is a three-dimensional computing and positioning system that relies on inertial sensors (accelerometer and gyroscope) to measure the movement information of carrier in real time [8]. Its operating mechanism relies on itself to process information, is not affected by external factors, and the signal accuracy is high. However, long-term operation and continuous integral calculation of IMU will lead to the accumulation of errors of inertial navigation system to some extent, and the accuracy of navigation will also decrease rapidly [9]. In practical application, the accuracy and stability of object positioning can not meet the requirements only by relying on one method. Among the current mainstream positioning technologies, GPS/INS combined positioning technology is recognized as the best combined positioning system. Combined navigation technology can make up for the shortcomings of a single system and provide higher accuracy and stability [10].

Due to the large area coverage of the current mobile hot spot communication network and the unstable positioning results caused by partial occlusion of GPS signals in the urban environment with large positioning requirements for personnel, the WIFI network data is combined with GPS and INS technology, and the RSSI parameters in the WIFI communication network are used to correct GPS occlusion interference signals in real time. Moreover, the cumulative error of INS system product decomposition calculation is calibrated [11]. At the same time, the INS system has the characteristics of high precision in a short time, which can compensate for a series of problems such as GPS signal loss and WIFI measurement error when GPS signal is interfered. Therefore, this paper proposes a combination positioning system of GPS/INS/WIFI for urban complex environment, which can not only meet the requirements of high precision, but also control the cost of the system within a reasonable range. Therefore, researchers have conducted a lot of research on the combinatorial algorithm of combinatorial positioning system. The INS/GPS/PLS integrated navigation and positioning system studied by Le Yang et al. utilizes fuzzy Kalman filter to improve the positioning accuracy of the positioning system [12]. Li Guang et al. also derived the Kalman filter of INS/GPS combined system and obtained the superiority of the combined system through simulation [13]. Li Yihe et al. compared the pseudo-distance loose combination filtering, tight combination filtering and tight combination adaptive filtering and found that the positioning accuracy of tight combination filtering was generally higher than that of loose combination [14]. Xu Zhenkai et al. studied the filtering algorithm in the loose combination mode of vehicle-mounted navigation, designed the trajectory discrimination-assisted adaptive Kalman filtering algorithm of GPS/INS integrated navigation system, and verified that this method effectively improved the stability of the filter and overcame the unreliable observed values caused by GPS position or speed hopping [15]]. However, GPS pseudo-distance parameters and the TOA parameters of WIFI positioning system are prone to multi-path interference, occlusion and electromagnetic wave interference in urban environment, thus resulting in strong nonlinear characteristics of measurement errors, and the traditional combined positioning filtering algorithm will reduce the positioning accuracy due to nonlinear errors [16].

In order to solve the above problems, this paper proposes a method for solving UKF positioning based on GPS/INS/WIFI combined system. Firstly, the characteristics of WIFI positioning technology are analyzed, and the INS positioning error model is established. The measurement equation under tight coupling is established by using the pseudo distance value of GPS and the RSSI parameter of WIFI system. At the same time, the state equation is established by using the INS error model, and then the state space equation of GPS/INS/WIFI combination positioning is established. Then, based on the theory of untracked Kalman filter, a tight combination location solution model based on GPS/INS/WIFI is established to achieve accurate positioning of personnel in complex environment.

2. GPS/INS/WIFI Personnel Positioning System

The global positioning system (GPS) has the characteristics of global, all-weather, high-precision and three-dimensional positioning, but it is blocked by obstacles in urban and other environments, resulting in low accuracy and poor reliability. Inertial navigation system (INS) is an independent and active positioning system with good dynamic performance and high short-term accuracy, but measurement errors will accumulate over time. Therefore, the WIFI positioning system based on rangefinding is built by using the WIFI network signals widely existing in the city, and then the combination positioning system of GPS/INS/WIFI is constructed. At the same time, the tight combination positioning solution model based on UKF is established on the basis of analyzing the respective positioning characteristics, so as to realize the complementary advantages and obtain good navigation accuracy and reliability.

2.1. Feature analysis of WIFI positioning technology

With the continuous development of "wireless city", the application of WIFI technology in our life is more and more extensive. At the same time, there is a growing demand in the location market for services such as critical equipment monitoring, critical patient care, real-time location queries, etc. GPS positioning needs to be realized in relatively empty, not dense buildings, less obstacles in the place to achieve accurate positioning, if used in urban environment or indoor, there are disadvantages such as low positioning accuracy, high power consumption. Therefore, the use of widely distributed and low-cost WIFI technology to locate targets in indoor or densely packed buildings can expand the application range of location services, which has positive social significance.

WIFI was not originally designed for location technology, however, the received signal strength (RSS) contained in the signals sent by hot spots (aps) or base stations periodically makes it possible to locate terminals. Currently, most WiFi-based location systems use RSS technology to realize location fingerprint recognition. Compared with current positioning technologies such as GPS, cellular positioning and dead reckoning, WIFI positioning has the following advantages:

1) Hot spots are widely distributed. WIFI hot spots can be distributed in indoor and outdoor environments, which provides the possibility for positioning on various occasions.

2) Low access threshold, WIFI positioning is built on the existing WIFI network, without network reconstruction or expansion, reducing the cost of use.

3) High flexibility, WIFI signal is less affected by non-line-of-sight (NLOS), even in dense urban areas and indoor environment can be used.

Then, WIFI positioning technology is affected by indoor wall obstacles and multi-path environment interference, which makes the RSSI ranging values measured by WIFI positioning technology have nonlinear errors, thus significantly reducing the wifi positioning accuracy [17].

2.2. INS system and its systematic error analysis

Inertial navigation system is a navigation parameter solving system composed of sensitive components gyroscope and accelerometer. The navigation coordinate system of the system is determined by the output value of the gyroscope. Finally, the position and speed of the carrier can be calculated according to the output value of the accelerometer. Inertial systems are generally divided into two categories: ring-mounted strapdown navigation systems. For the ring-frame system, the rotation between the sensor and the carrier is independent of each other, the accelerometer and gyroscope are placed on the known reference platform, and the system carries out the measurement and calculation process in the stable coordinate system. The advantages of ring-rack system are high accuracy and easier coordinate correction. In the correction process, the earth gravity field can be used for automatic correction without additional coordinate conversion. Its disadvantages are that the whole ring-rack system is large in volume, heavy in structure and high in cost. For the strapdown system, the sensor is fixed on the carrier, and the acceleration and velocity of the moving target are calculated in the inertial system by means of coordinate transformation. Taking into account personnel positioning requirements, strapdown inertial systems with small, lightweight MEMS gyroscopes and accelerometers not only reduce cost, but also improve reliability, has become the main inertial system.

However, there are some errors in the manufacturing of MEMS inertial devices, which are greatly affected by temperature and device vibration, and will result in measurement errors. These errors fall into the following categories:

1) Installation error. In actual installation, any assembly will have installation errors. The installation of the inertial component cannot coincide with the installation of the initial carrier coordinate system, so the errors will be generated.

2) Initial value error. The input of these data, including the alignment of initial position, speed and attitude, requires manual measurement, so there are some problems resulting in reduced accuracy.

3) Carrier motion interference error. The motion interference is mainly caused by the vibration of the carrier in high-speed operation. The more high precision the system has, the greater the influence in complex environment.

During the modeling analysis, only several major error sources were analyzed, and gyroscopic drift and zero position error of accelerometer were considered in the derivation [18].

Let the velocity error in the X direction be, the Y direction be, the Z direction be, the longitude error be, the latitude error be, the height error be, the curvature radius of the meridian circle be, the curvature radius of the meridian circle be, and

$$\begin{cases} R_m = R_e\left(1-2e+3e\sin^2\varphi\right) \\ R_n = R_e+\left(1+e\sin^2\varphi\right) \end{cases} \tag{1}$$

Where, represents the semi-major axis of the ellipsoidal model, and R_e represents the ellipsoid. The platform error Angle equation is:

$$\begin{cases} \dot{\alpha} = -\sigma V_y/\left(R_m+H\right)-\left(\omega_{ie}\cos\varphi+V_x/\left(R_n+H\right)\right)\gamma \\ \quad +\left(\omega_{ie}\sin\varphi+V_x\tan\varphi/\left(R_n+H\right)\beta+\varepsilon_x \right. \\ \dot{\beta} = \sigma V_x/\left(R_n+H\right)-\left(\omega_{ie}\sin\varphi+V_x\tan\varphi/\left(R_n+H\right)\right)\alpha \\ \quad -V_y\gamma/\left(R_m+H\right)-\omega_{ie}\sin\varphi\sigma\varphi+\varepsilon_y \\ \dot{\gamma} = \sigma V_x\tan\varphi/\left(R_n+H\right)+\left(\omega_{ie}\cos\varphi+V_x/\left(R_n+H\right)\right)\alpha \\ \quad +V_y\beta/\left(R_m+H\right)+\omega_{ie}\cos\varphi\sigma\varphi+\varepsilon_z \end{cases} \tag{2}$$

Where, ω_{ie} is the rotation rate of the earth, H is the height, and ε_x, ε_y and ε_z are the constant errors of the gyroscope respectively.

The velocity error equation is:

$$\begin{cases} \sigma\dot{V}_x = \left(V_y\tan\varphi/\left(R_m+H\right)-V_z/\left(R_m+H\right)\right)\sigma V_x+ \\ \quad \left(2\omega_{ie}\sin\varphi+V_x\tan\varphi/\left(R_n+H\right)\right)\sigma V_y-g\beta+ \\ \quad \left(2\omega_{ie}\cos\varphi V_y+V_xV_y\sec^2\varphi/\left(R_n+H\right)+2\omega_{ie}\sin\varphi V_z\right)\sigma\varphi \\ \quad -\left(2\omega_{ie}\cos\varphi+V_x/\left(R_n+H\right)\right)\sigma V_z+\Delta A_x \\ \sigma\dot{V}_y = \left(-2\omega_{ie}\sin\varphi-2V_x\tan\varphi/\left(R_n+H\right)\right)\sigma V_x-V_z\sigma V_y/\left(R_m+H\right) \\ \quad +g\alpha-\left(2\omega_{ie}\cos\varphi V_x+V_x^2\sec^2\varphi/\left(R_n+H\right)\right)\sigma\varphi \\ \quad -V_y\sigma V_z/\left(R_m+H\right)+\Delta A_y \\ \sigma\dot{V}_z = \left(2\omega_{ie}\cos\varphi+2V_x/\left(R_n+H\right)\right)\sigma V_x+2V_y\sigma V_y/\left(R_m+H\right) \\ \quad -2\omega_{ie}\sin\varphi V_x\sigma\varphi+2g\sigma H/R+\Delta A_z \end{cases} \tag{3}$$

Where, ΔA_x, ΔA_y and ΔA_z is the constant error of the accelerometer;

The position error equation is:

$$\begin{cases} \sigma\dot{\varphi} = \sigma V_y/\left(R_m+H\right) \\ \sigma\dot{\lambda} = \sigma V_x sec\varphi/\left(R_n+H\right)+ \\ \quad V_x tan\varphi sec\varphi\sigma\varphi/\left(R_n+H\right) \\ \sigma\dot{H} = \sigma V_z \end{cases} \tag{4}$$

The above four equations constitute the error equation of the inertial navigation system, and then the influence of error sources on various navigation parameters can be obtained by solving the error equation. The solution method can be to use these equations to write down the state of Kalman Filter and measurement equation, perform optimal state estimation, obtain the estimation of the changes of these navigation parameters, and then carry out error compensation, so as to improve the accuracy of the navigation system.

2.3. GPS/INS/WIFI personnel tight combination mode

In the tight combination mode, the GPS pseudo-distance and carrier phase double difference observation equation and the position observation equation given by INS were solved in combination. Tight combination is a relatively complicated combination mode. In this combination mode, the satellite provided by GPS receiver is used to locate the original information, such as pseudo range rate, pseudo range and Doppler frequency, etc. Compared with tight combination navigation system, it has higher accuracy of navigation solution. At the same time, the tight combination system uses the RSSI ranging value measured in real time by WIFI system to construct the measurement equation synchronously. At the same time, when some GPS signals of the carrier are blocked by the outside world and WIFI signals are interfered, the tight integrated navigation system can still make use of its limited GPS and WIFI information to conduct navigation calculation, which has stronger anti-interference ability compared with the traditional loose integrated navigation system. The solution process of INS/GPS/WIFI tight combination positioning is shown in Figure 1.

Figure 1. Flow chart of INS/GPS/WIFI tight combination

The model is solved according to the described position of INS moving target, which can be expressed as follows:

$$\begin{cases} \boldsymbol{P}_{k+1}^{n} = \boldsymbol{P}_{k}^{n} + \boldsymbol{V}_{k}^{n} T + \left(\boldsymbol{C}_{b}^{n} \boldsymbol{a}_{k}^{b} - \boldsymbol{g}^{n} \right) T^{2} / 2 \\ \boldsymbol{V}_{k+1}^{n} = \boldsymbol{V}_{k}^{n} + \left(\boldsymbol{C}_{b}^{n} \boldsymbol{a}_{k}^{b} - \boldsymbol{g}^{n} \right) T \end{cases} \tag{5}$$

Where, P and V respectively represent the position and velocity of personnel in n system (navigation coordinate system), a^b the acceleration of personnel in b system (carrier coordinate system), and T is the sampling period of INS. The total differential calculation under the parameters of Equation (5) is carried out, and the differential results are as follows:

$$\begin{cases} \sigma \boldsymbol{P}_{k+1}^{n} = \sigma \boldsymbol{P}_{k}^{n} + \sigma \boldsymbol{V}_{k}^{n} T - \left(\boldsymbol{C}_{b}^{n} \boldsymbol{a}_{k}^{b} \times \right) \dfrac{T^{2}}{2} \sigma \boldsymbol{A}_{\boldsymbol{k}} + \boldsymbol{C}_{b}^{n} \dfrac{T^{2}}{2} \sigma \boldsymbol{a}_{k}^{b} \\ \sigma \boldsymbol{V}_{k+1}^{n} = \sigma \boldsymbol{V}_{k}^{n} - \left(\boldsymbol{C}_{b}^{n} \boldsymbol{a}_{k}^{b} \times \right) T \sigma \boldsymbol{A}_{\boldsymbol{k}} + \boldsymbol{C}_{b}^{n} T \sigma \boldsymbol{a}_{k}^{b} \end{cases} \tag{6}$$

Where, $\sigma \boldsymbol{P}^{n}$ and $\sigma \boldsymbol{V}^{n}$ are the position error vector and velocity error vector of personnel in the navigation coordinate system respectively. Matrix $\boldsymbol{C}_{b}^{n}$ is the attitude matrix of b system relative to n system, $\sigma \boldsymbol{A}$ is the attitude error vector, $\sigma \boldsymbol{a}^{b}$ is the measurement noise of SINS accelerometer, and 6 is the antisymmetric matrix of acceleration vector.

Therefore, the state vector of the system state equation is set as,

$$\boldsymbol{x}_{k} = \left[\sigma \boldsymbol{P}_{k}^{n} \quad \sigma \boldsymbol{V}_{k}^{n} \quad \sigma \boldsymbol{A}_{k} \right]^{\mathrm{T}} \tag{7}$$

Then the equation of state can be expressed as,

$$\boldsymbol{x}_{k+1} = \boldsymbol{F}_{k,k+1} \boldsymbol{x}_{k} + \boldsymbol{G}_{k} \boldsymbol{W}_{k} \tag{8}$$

Where, $\boldsymbol{W}_{k}$ is the system noise vector $\boldsymbol{W}_{k} = \left[\boldsymbol{\omega}_{\varepsilon} \quad \sigma \boldsymbol{a}^{b} \right]_{k}^{\mathrm{T}}$ of the equation of state. $\boldsymbol{\omega}_{\varepsilon}$ is the measurement noise of SINS gyroscope. $\boldsymbol{G}_{k}$ is the input matrix of the system model and $\boldsymbol{F}_{k,k+1}$ is the transfer matrix of the state vector. Then we can be simplified to,

$$\boldsymbol{F}_{k,k+1} = \begin{bmatrix} \boldsymbol{I}_{3\times3} & T\boldsymbol{I}_{3\times3} & -\left(\boldsymbol{C}_{b}^{n} \boldsymbol{a}^{b} \times \right) T^{2} / 2 \\ 0_{3\times3} & \boldsymbol{I}_{3\times3} & -\left(\boldsymbol{C}_{b}^{n} \boldsymbol{a}^{b} \times \right) T \\ 0_{3\times3} & 0_{3\times3} & \boldsymbol{I}_{3\times3} \end{bmatrix}_{k} \tag{9}$$

$$\boldsymbol{G}_{k} = \begin{bmatrix} 0_{3\times3} & \boldsymbol{C}_{b}^{n} T^{2} / 2 \\ 0_{3\times3} & \boldsymbol{C}_{b}^{n} T \\ \boldsymbol{C}_{b}^{n} & 0_{3\times3} \end{bmatrix}_{k} \tag{10}$$

Where, $\boldsymbol{I}_{3\times3}$ is the identity matrix of order 3. According to the pseudo-distance ranging model of GPS satellite and moving target and the RSSI ranging parameters of WIFI, the ranging error transfer equation is defined as follows:

$$\begin{cases} \varepsilon_{d,G}\left(k+1 \right) = \varepsilon_{d,G}\left(k \right) + \nabla_{\varepsilon,G}\left(k \right) \\ \varepsilon_{d,W}\left(k+1 \right) = \varepsilon_{d,W}\left(k \right) + \nabla_{\varepsilon,W}\left(k \right) \end{cases} \tag{11}$$

Where, $\nabla_{\varepsilon,G}\left(k \right)$ and $\nabla_{\varepsilon,W}\left(k \right)$ are Gaussian white noise.

Therefore, according to formula (8) and (11), the equation of state of INS/GPS/WIFI tightly coupled combined positioning system can be written as

$$\begin{aligned} \underbrace{\begin{bmatrix} x\left(k+1 \right) \\ \varepsilon_{d,G}\left(k+1 \right) \\ \varepsilon_{d,W}\left(k+1 \right) \end{bmatrix}}_{\boldsymbol{x}^{t}\left(k+1 \right)} &= \underbrace{\begin{bmatrix} \boldsymbol{F}_{k,k+1} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\boldsymbol{F}_{k,k+1}^{t}} \underbrace{\begin{bmatrix} x\left(k \right) \\ \varepsilon_{d,G}\left(k \right) \\ \varepsilon_{d,W}\left(k \right) \end{bmatrix}}_{\boldsymbol{x}^{t}\left(k \right)} \\ &+ \underbrace{\begin{bmatrix} \boldsymbol{G}_{k} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\boldsymbol{G}_{k}^{t}} \underbrace{\begin{bmatrix} \boldsymbol{W}_{k} \\ \nabla_{\varepsilon,G}\left(k \right) \\ \nabla_{\varepsilon,W}\left(k \right) \end{bmatrix}}_{\boldsymbol{W}^{t}\left(k \right)} \end{aligned} \tag{12}$$

Where, $\boldsymbol{W}^{t}\left(k \right)$ is zero mean Gaussian white noise, its variance is $\boldsymbol{Q}(\mathrm{k})$, and symbol t represents tight coupled combined positioning.

According to the INS/GPS/WIFI combined positioning system, the coordinate of the mobile node measured by INS is $\left(x_{I}, y_{I}, z_{I} \right)$. At the same time, the 3D position coordinate of the I-th GPS satellite that can receive signals is set as $\left(x_{i}, y_{i}, z_{i} \right)$. According to the mathematical expression of the distance solving formula, the pseudo-distance value $\rho_{\mathrm{I}i}$ measured by INS between the i-th GPS satellite and the mobile node can be calculated as follows:

$$\rho_{\mathrm{I}i} = \left(\left(x_{\mathrm{I}} - x_{i} \right)^{2} + \left(y_{\mathrm{I}} - y_{i} \right)^{2} + \left(z_{\mathrm{I}} - z_{i} \right)^{2} \right)^{1/2} \tag{13}$$

The first-order Taylor expansion under coordinate point $\left(x_{I}, y_{I}, z_{I} \right)$ is carried out on Equation (13), and the calculation results are as follows:

$$\rho_{\mathrm{I}i} = \left(\left(x_{\mathrm{I}} - x_{i} \right)^{2} + \left(y_{\mathrm{I}} - y_{i} \right)^{2} + \left(z_{\mathrm{I}} - z_{i} \right)^{2} \right)^{1/2} + \frac{\partial \rho_{\mathrm{I}i}}{\partial x} \delta x + \frac{\partial \rho_{\mathrm{I}i}}{\partial y} \delta y + \frac{\partial \rho_{\mathrm{I}i}}{\partial z} \delta z \tag{14}$$

According to the GPS pseudo-distance ranging model described in formula (14), the GPS ranging value between the I-th GPS satellite and the mobile node can be obtained as follows:

$$\rho_{\mathrm{G}i} = d_{i} + \varepsilon_{d} + \upsilon_{d} \tag{15}$$

Where, is the true distance from the i-th GPS satellite to the mobile node, and ε_{d} is the NLOS error. υ_{d} is the measurement noise. Therefore, the difference value $\rho_{G,i}$ between the two ranging values can be defined as,

$$\rho_{G,i} = \rho_{1,i} - \rho_{\mathrm{G},i} = \frac{\partial \rho_{1,i}}{\partial x} \delta x + \frac{\partial \rho_{1,i}}{\partial y} \delta y + \frac{\partial \rho_{1,i}}{\partial z} \delta z - \varepsilon_{d} - \upsilon_{d} \tag{16}$$

Similarly,

$\frac{\partial\rho_{\mathrm{I},i}}{\partial x}=\frac{x-x_i}{\rho_{\mathrm{I},i}},\frac{\partial\rho_{\mathrm{I},i}}{\partial y}=\frac{y-y_i}{\rho_{\mathrm{I},i}},\frac{\partial\rho_{\mathrm{I},i}}{\partial z}=\frac{z-z_i}{\rho_{\mathrm{I},i}}$,the difference between WIFI ranging value and ranging value between INS and WIFI base station $\rho_{W,i}$ can be written as,

$$\rho_{W,i}=\rho_{\mathrm{I}i}-\rho_{\mathrm{W},i}=\frac{\partial\rho_{\mathrm{I},i}}{\partial x}\delta x+\frac{\partial\rho_{\mathrm{I},i}}{\partial y}\delta y+\frac{\partial\rho_{\mathrm{I},i}}{\partial z}\delta z-\varepsilon_d-\upsilon_d \quad (17)$$

Where, $\frac{\partial\rho_{\mathrm{I},i}}{\partial x}=\frac{x-x_i}{\rho_{\mathrm{I},i}},\frac{\partial\rho_{\mathrm{I},i}}{\partial y}=\frac{y-y_i}{\rho_{\mathrm{I}i}},\frac{\partial\rho_{\mathrm{I},i}}{\partial z}=\frac{z-z_i}{\rho_{\mathrm{I}i}}$, so the measurement equation of INS/GPS/WIFI tightly coupled combined positioning model is shown in the following equation.

$$\boldsymbol{z}^t\left(k\right)=\boldsymbol{H}_k^t\boldsymbol{x}^t\left(k\right)+\boldsymbol{V}^t\left(k\right) \quad (18)$$

Where, $\boldsymbol{z}^t\left(k\right)=\left[\rho_{\mathrm{G},1} \quad \cdots \quad \rho_{G,n} \quad \rho_{\mathrm{W},1} \quad \cdots \quad \rho_{W,n}\right]^{\mathrm{T}}$,, $\boldsymbol{V}^t\left(k\right)=\left[\upsilon_{d1} \quad \upsilon_{d2} \quad \cdots \quad \upsilon_{d2n}\right]^{\mathrm{T}}$, $\boldsymbol{H}_k^t=\begin{bmatrix}\partial\rho_{\mathrm{I}1}/\partial x & \partial\rho_{\mathrm{I}1}/\partial y & \partial\rho_{\mathrm{I}1}/\partial z & & -1\\ \vdots & \vdots & \vdots & \mathbf{0}_{n\times6} & \vdots\\ \partial\rho_{\mathrm{I}n}/\partial x & \partial\rho_{\mathrm{I}n}/\partial y & \partial\rho_{\mathrm{I}n}/\partial z & & -1\\ \partial\rho_{\mathrm{I}1}/\partial x & \partial\rho_{\mathrm{I}1}/\partial y & \partial\rho_{\mathrm{I}1}/\partial z & & -1\\ \vdots & \vdots & \vdots & \mathbf{0}_{n\times6} & \vdots\\ \partial\rho_{\mathrm{I}n}/\partial x & \partial\rho_{\mathrm{I}n}/\partial y & \partial\rho_{\mathrm{I}n}/\partial z & & -1\end{bmatrix}$,According to equations (14) and (18), the state space equation of INS/GPS/WIFI tightly coupled combined positioning model is finally established.

3. Combine the Positioning Algorithm

3.1. Untracked Kalman filter

Now the main problem facing Kalman filter is the processing of nonlinear measurement model and nonlinear processing mode, which can be described from the perspective of probability distribution as:

For the state we need to estimate, when the variance is, k meets a Gaussian distribution with such a mean value, this is our post verification at k time. Meanwhile, if we consider the whole Kalman filtering process iteratively, take this post verification as the starting point, and estimate the variance and mean value of the state at k+1 time with certain knowledge, This is the prediction process of Kalman filter. When the transformation is linear, the predicted result is still Gaussian distribution, but it is common in reality that the processing and measurement models are nonlinear, so the result is an irregular distribution. The premise of using Kalman filter is that the processing state satisfies the Gaussian distribution. In order to solve this problem, Kalman waves need to be changed. Untracked Kalman filtering is to find a Gaussian distribution approximate to the real distribution [19], while extended Kalman filtering is to find a linear function to approximate the nonlinear function [20]. The premise of finding a Gaussian distribution that approximates the real distribution is to find a Gaussian distribution that has the same mean and variance as the real distribution, and this requires the use of lossless transformation (UT transformation).

3.1.1. Lossless transformation

Lossless transformation is to approximate a Gaussian distribution by using a certain number of parameters. The basic principle of lossless transformation is as follows: select some points in the original distribution according to a certain law, so that the covariance and mean of each point are equal to the covariance and mean of the original distribution. On this basis, each point is substituted into a nonlinear function, and the set of value points is formed. The lossless transformation can be performed by using the set of points, and the mean value and covariance of the transformation can be obtained.

These sigma points generated by certain means can represent the current distribution, and then these points are transformed into new points through the nonlinear function, namely the system model, and then based on these new sigma points, a Gaussian distribution is calculated with weights.

The basic principle of UT transformation is as follows: Suppose a nonlinear system y=f(x), where x is an n-dimensional state vector, and its mean value and variance are known to be, then 2n+1 Sigma points can be constructed through UT transformation, and corresponding weights can be constructed at the same time to obtain the statistical characteristics of y [21].

The calculation formula for constructing sigma point set is as follows:

$$\begin{gathered}x_0=\bar{x},i=0\\ x_i=\bar{x}+\left(\sqrt{\left(n+\lambda\right)P_x}\right)_i,i=1\cdots n\\ x_i=\bar{x}-\left(\sqrt{\left(n+\lambda\right)P_x}\right)_{i-n},i=n+1\cdots 2n\end{gathered} \quad (19)$$

Where the λ is a scaling factor, and according to the formula, the larger the λ, the further away the sigma point is from the mean of the states, and the smaller the λ, the closer the sigma point is to the mean of the states.

$$\lambda=\alpha\left(n^2+k\right)-n \quad (20)$$

$\left(\sqrt{\left(n+\lambda\right)P_x}\right)_i$ represents the ith column of the matrix root $\left(\sqrt{\left(n+\lambda\right)P_x}\right)_{i-n}$.

The mean weight W_i^m and variance weight W_i^c are set to approximate the post-verified mean and variance of the nonlinear function. The selected sigma sampling point set $\left\{x_i\right\},i=0,1,\cdots L$ is used to carry out nonlinear function transfer to obtain: $y_i=f\left(x_i\right)$, where is the corresponding point of sigma sampling after nonlinear function transfer. According to the weighted statistical linear regression technique, the statistical characteristics of y can be approximately obtained:

$$\begin{aligned} \overline{y} &= \sum_{0}^{L} W_i^m y_i \\ P_{yy} &= \sum_{0}^{L} W_i^c \left(y_i - \overline{y}\right)\left(y_i - \overline{y}\right)^T \\ P_{xy} &= \sum_{0}^{L} W_i^c \left(x_i - \overline{x}\right)\left(x_i - \overline{x}\right)^T \end{aligned} \tag{21}$$

3.1.2. Sampling Policy

Since the sampling methods of Sigma points are different, the variance weights and average weights of Sigma points are also different. As a result, estimates of the UT transform may vary, but overall, its accuracy is comparable to the quadratic accuracy of the Taylor series.

In order to ensure that in the random variable after sampling, the Sigma sampling points still retain the characteristics necessary for the original variable, so the sampling points must be selected in accordance with:

$$g\left[\left\{x_i, W_i^m, W_i^c\right\}, L, P_x\left(x\right)\right] = 0 \tag{22}$$

If the density function $P_x\left(x\right)$ has only one or two order matrices, it can be written as:

$$g\left[\left\{x_i, W_i^m, W_i^c\right\}, L, P_x\left(x\right)\right] = \begin{bmatrix} \sum_{i=0}^{L} W_i^m - land \sum_{i=0}^{L} W_i^m - 1 \\ \sum_{i=0}^{L} W_i^m x_i - \overline{x} \\ \sum_{i=0}^{L} W_i^c \left(x_i - \overline{x}\right)\left(x_i - \overline{x}\right)^T - P_x \end{bmatrix} = 0 \tag{23}$$

3.1.3. Proportional correction symmetric sampling

Scaling correction algorithm:

$$\begin{aligned} x_i^{'} &= x_0 + \alpha\left(x_i - x_o\right) \\ \left(W_i^m\right)^{'} &= \begin{cases} W_0^m / \alpha^2 + 1 - 1/\alpha^2, i = 0 \\ W_i^m / \alpha^2, i \neq 0 \end{cases} \\ \left(W_i^c\right)^{'} &= \begin{cases} \left(W_i^m\right)^{'} + \left(1 + \beta - \alpha^2\right), i = 0 \\ \left(W_i^m\right)^{'}, i \neq 0 \end{cases} \end{aligned} \tag{24}$$

In the formula, α is the scaling factor; $0 \leq \alpha \leq 1$, the value of control α can control the range of Sigma point set, which is usually set as a small positive number. β reflects the higher-order characteristics of state history information, which is optimal for Gaussian distribution $\beta = 2$.

The proportional correction algorithm is applied in symmetric sampling to form a proportional correction symmetric sampling strategy:

$$\begin{cases} x_0^{'} = \overline{x} \\ x_i^{'} = \overline{x} + \left(\sqrt{\left(n+k\right)P_X}\right)_i, i = 1, 2, \ldots n \\ x_i^{'} + n = \overline{x} - \left(\sqrt{\left(n+k\right)P_X}\right)_i \end{cases} \tag{25}$$

Corresponding weight:

$$\begin{aligned} \left(W_i^m\right)^{'} &= \begin{cases} \dfrac{\lambda}{\left(n+\lambda\right)}, i = 0 \\ \dfrac{1}{2\left(n+\lambda\right)}, i \neq 0 \end{cases} \\ \left(W_i^c\right)^{'} &= \begin{cases} \dfrac{\lambda}{\left(n+\lambda\right)} + 1 + \beta - \alpha^2, i = 0 \\ \dfrac{1}{2\left(n+\lambda\right)}, i \neq 0 \end{cases} \end{aligned} \tag{26}$$

Nonlinear system considering Gaussian white noise:

$$\begin{cases} x_{k+1} = f\left(x_k\right) + w_k \\ z_k = h\left(x_k\right) + v_k \end{cases} \tag{27}$$

3.2. Untraced Kalman filtering algorithm flow

Assume that the initial state estimation and estimated variance of the filter are:

$$\begin{cases} \hat{x}_0 = E\left(x_0\right) \\ P_{0,0} = E\left(x_0 - \hat{x}_0\right)\left(x_0 - \hat{x}_{0,0}\right)^T \end{cases} \tag{28}$$

Time update: Assuming the estimated state value $\hat{x}_{k|k}$ and estimated variance $P_{k|k}$ at moment k, 2n+1 Sigma sampling points $x_i^{'}$ and corresponding weights $\left(W_i^m\right)^{'}$ and $\left(W_i^c\right)^{'}$ can be obtained by proportional modification of the symmetric sampling strategy, and then the sampling points are transferred to $\gamma_{k+1|k}^i = f\left(x_i^{'}\right)$ by nonlinear state function.

The mean and variance of state prediction are as follows:

$$\begin{cases} \hat{x}_{k+1|k} = \sum_{i=0}^{2n} \left(W_i^m\right)^{'} \gamma_{k+1|k}^i \\ P_{k+1|k} = \sum_{i=0}^{2n} \left(W_i^c\right)^{'} \left(\gamma_{k+1|k}^i - \hat{x}_{k+1|k}\right)\left(\gamma_{k+1|k}^i - \hat{x}_{k+1|k}\right)^T + Q_k \end{cases} \tag{29}$$

After nonlinear measurement function transfer:

$$\zeta^{i^{k+1|k}} = h\left(\zeta_i^{'}\right) \tag{30}$$

One-step prediction of mean, variance and covariance of measurement variables:

$$\begin{cases} \hat{z}_{k+1|k} = \sum_{i=0}^{2n} \left(W_i^m\right)' \zeta_{k+1|k} \\ P_{zz,k+1|k} = \sum_{i=0}^{2n} \left(W_i^c\right)' \left(\zeta_{k+1|k}^i - \hat{z}_{k+1|k}\right)\left(\zeta_{k+1|k}^i - \hat{z}_{k+1|k}\right)^T + R_{k+1} \\ P_{xz,k+1|k} = \sum_{i=0}^{2n} \left(W_i^c\right)' \left(\gamma_{k+1|k}^i - \hat{x}_{k+1|k}\right)\left(\zeta_{k+1|k} - \hat{z}_{k+1|k}\right)^T \end{cases} \quad (31)$$

According to the measured value at time k+1, filtering gain K_{k+1}, moment state estimation and estimation variance at time k+1 can be obtained:

$$\begin{cases} \hat{x}_{k+1} = \hat{x}_{k+1|\,k} + K_{k+1}\left(z_{k+1} - \hat{z}_{k+1|\,k}\right) \\ K_{k+1} = P_{\bar{x}_{k+1}\bar{z}_{k+1}}\left(P_{\bar{z}_{k+1}}\right)^{-1} \\ P_{k+1} = P_{k+1|\,k} - K_{k+1}\left(P_{\bar{z}_{k+1}}\right)^{-1} K_{k+1}^{-1} \end{cases} \quad (32)$$

Finally, an asynchronous data fusion algorithm is established according to the state space model and UKF. Compared with KF (Kalman filter) and EKF (extended Kalman filter) algorithms, UKF algorithm will significantly improve the positioning accuracy of the combined positioning system.

4. Experiment and analysis

4.1. Introduction to the experimental device

First design the overall scheme of the experimental device:

Figure 2. Schematic diagram of the overall scheme of the device

IMU collects the inertia data of human body movement in real time, and the GPS positioning module outputs the pseudo-distance data. The WIFI measuring module uses the WIFI intensity measured in real time to calculate the RSSI ranging, and finally transmits the data of the three to the MCU through I2C wired communication mode. The MCU uses WIFI function to upload data to MySQL database on the cloud server. The upper PC connects to the network and obtains data from MySQL in the cloud through Pycharm programming environment based on Python. Then the obtained data is analyzed and processed by Kalman algorithm using matlab.

The physical figure of the wearing mode of the experimental device is shown in Figure 4.3. The device is attached to the chest, and the installation mode of the IMU is vertical, that is, the Z-axis is perpendicular to the ground. At the same time, GPS and WIFI modules are installed on the experimental device, and the microcontroller will be connected to a mobile power supply through MicroUSB port.

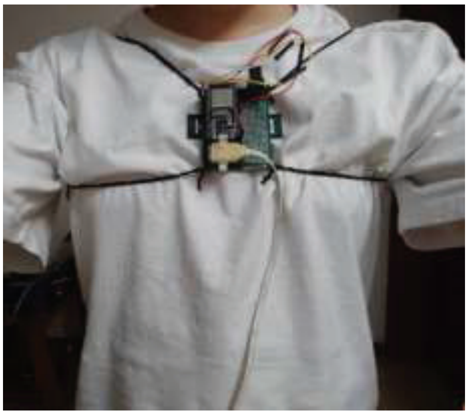

Figure 3. Device wearing diagram

The device was worn on the chest in the experiment because the motion states of various parts of the body were not completely the same when people were exercising. The arm and leg would swing, but the arm swing was not directly related to walking. The leg swing could be subdivided into thigh swing, calf swing and foot swing, and the speed and range of the three different positions of the swing had their own characteristics. Therefore, the anterior thoracic cavity was used as the fixed installation position of the experimental device. The following is the actual picture of the experiment:

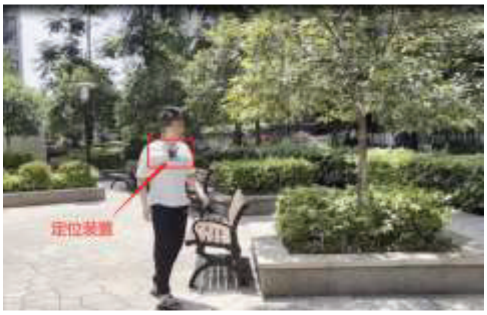

Figure 4. Actual scene of the experiment

During the experiment, the experimenter wore the positioning device and walked freely in the complex terrain area, and finally got the positioning experimental data.

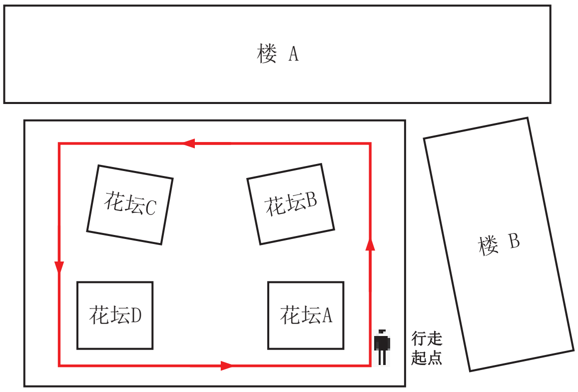

Figure 5. Schematic diagram of experimental scene and experimental route layout

4.2. Analysis of experimental results

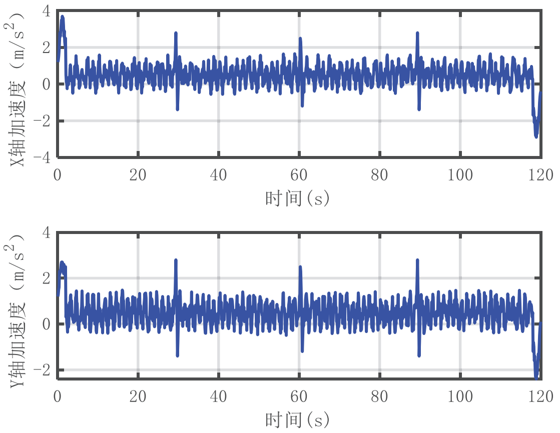

Figure 6. Data curve of INS acceleration measurement

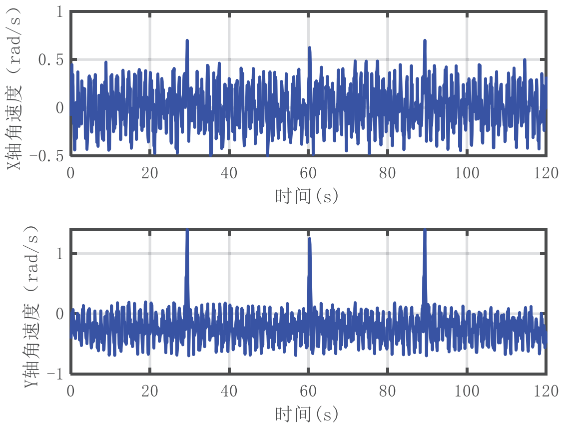

Figure 7. Measurement data curve of INS gyroscope

Figure 6 and Figure 7 are the actual data collected by the sensor of INS system under the wearable integrated positioning experiment platform of the above introducer, and the actual measurement data curves of the acceleration and gyroscope of INS system respectively. As the experiment was carried out by human wearers, spikes appeared in the data measured by the accelerometer when people started to walk and move through the corner. The gyro measurements only show spikes when the person walks around the corner.

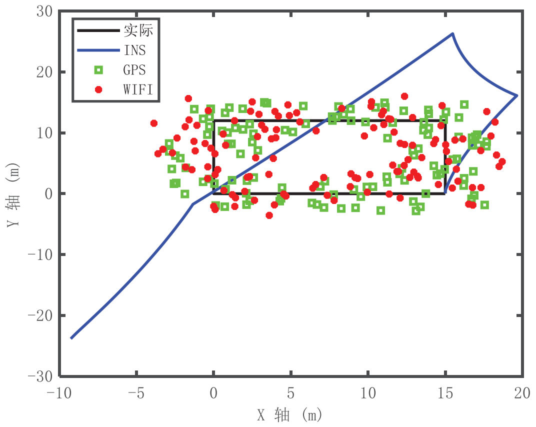

Figure 8. Positioning results of INS, GPS and WIFI separately

Figure 8 shows the results obtained under the location measurement of INS, GPS and WIFI systems in separate experiments. As can be clearly seen from the figure, the blue line, that is, the final position positioned by the INS system, differs greatly from the end point of the actual track, and the positioning effect of the overall trajectory is significantly different from that of GPS and WIFI systems, mainly because the positioning of the INS system does not depend on external information, and errors will accumulate and grow until divergent. While GPS positioning system and WIFI positioning system positioning effect is similar, but the overall positioning effect of both is not ideal.

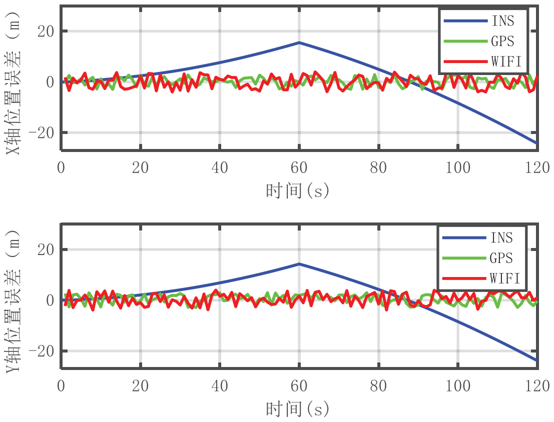

Figure 9. Individual positioning error curves of INS, GPS and WIFI

Figure 9 shows the positioning error results of INS, GPS and WIFI systems in separate experimental positioning measurement. In the figure, the errors of the INS positioning system are relatively small and stable in the early 20s. From the 20s to the 80s, errors appeared in a process of increasing to decreasing, and after the 80s, errors accumulated and gradually increased. While GPS and WIFI positioning system error has been kept in a smaller and stable state than INS system positioning error. It can also be seen from the figure that the positioning error of GPS and WIFI positioning system is kept within 4m.

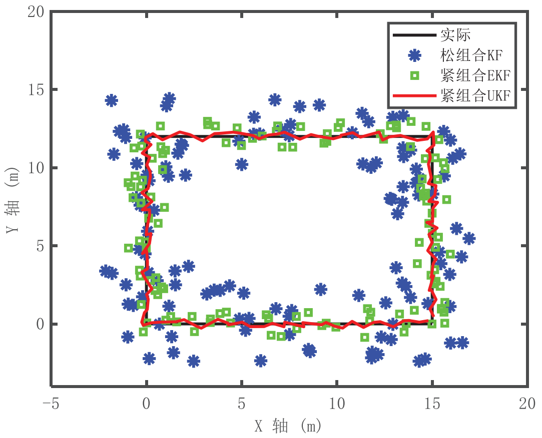

Figure 10. Positioning results of different positioning algorithms

It can be clearly seen from FIG. 10 that the red line in the figure can effectively and accurately track the actual track even if it is processed by UKF filtering algorithm with tight combination, and EKF filtering algorithm also has good tracking effect under tight combination, while KF filtering algorithm processing results error is obviously larger than the other two. But the EKF filtering algorithm is only the first order linearization of the nonlinear function, and EKF has to solve the nonlinear equation Jacobi matrix, so when the positioning model of the combined positioning system has strong nonlinear, the positioning accuracy of the EKF filtering algorithm will be reduced or even divergent.

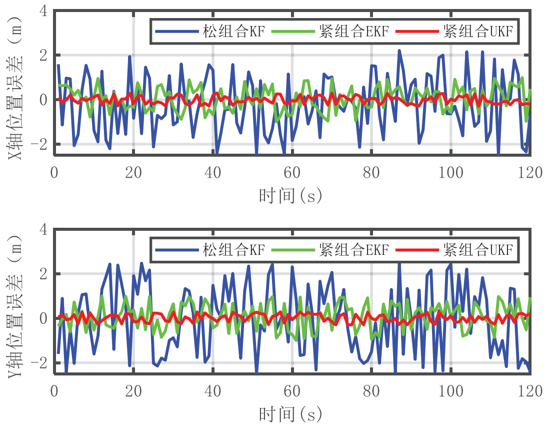

Figure 11. Positioning error curves of different positioning algorithms

Figure 11 shows the positioning errors using loose combination and KF filtering algorithm, tight combination and EKF filtering algorithm, and tight combination and UKF filtering algorithm. Among them, the positioning errors under the combination of tight combination and UKF filtering algorithm are represented by red dotted lines, while the positioning errors under the combination of loose combination and KF filtering algorithm and tight combination and EKF filtering algorithm are represented by blue and green dotted lines respectively. As can be seen from the figure, the maximum positioning error is 0.45m when tight combination is combined with UKF filtering algorithm, while the maximum positioning error is 1.02m and 4.1m when loose combination is combined with KF filtering algorithm and tight combination is combined with EKF filtering algorithm. Therefore, compared with extended Kalman filter and Kalman filter, the positioning accuracy of untraced Kalman filter is improved by 56% and 89%, respectively.

5. Conclusion

Aiming at the problem of poor positioning accuracy in indoor environment, this paper proposes a tight combination combination positioning method based on GPS/INS/WIFI, and uses UKF filtering algorithm to process positioning data. The experiment was carried out by using the wearable integrated positioning experimental platform, and the individual measurement data and error results of GPS, INS and WiFi systems were comprehensively compared in the real and complex experimental environment. The positioning data and errors of GPS/INS/WIFI combined positioning system are respectively processed by the positioning results of loose combined KF filter, tight combined EKF filter and tight combined UKF filter. The results show that: The positioning accuracy of GPS/INS/WIFI combined positioning system is higher than that of a single positioning system, and the positioning accuracy of GPS/INS/WIFI combined system is the highest after the tight combination of UKF filtering algorithm, which can be significantly adapted to indoor environment with complex interference, and has high positioning stability and accuracy. The maximum positioning error is 0.45m. Compared with extended Kalman filter and Kalman filter, the positioning accuracy of untraced Kalman filter is increased by 56% and 89%, respectively, which can meet the requirements of field use. In the follow-up work, we will continue to study the combination mode and filtering algorithm processing of higher positioning accuracy under the combination positioning, so as to further improve the practicability and robustness of the combination positioning system.

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