Tightly Coupled Model for Indoor Positioning based on UWB/INS

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Abstract

In this paper a tightly coupled indoor positioning system combining Ultra-Wideband (UWB) measurements with low-cost MEMS inertial navigation system (INS) measurements is proposed. Wireless sensor signal outage and severe multipath propagation very often lead to ranging errors, which make pure UWB-based localization less effective. Moreover, inertial sensors have their drift with time. A tightly coupled system is uesd to estimate moving target position and attitude in the indoor conditions. In order to eliminate the clock error, Time Difference of Arrival (TDOA) approach is used. Dynamic and static tests are carried on for the tightly coupled approach. Experimental results show that the tightly coupled indoor positioning system can improve the single system position accuracy and achieve the position and attitude real-time tracking of moving targets.

Keyword: *Ultra-Wideband Wireless; indoor position; inertial navigation; tightly coupled system*

1. Introduction

Location-awareness is rapidly becoming an essential feature of many commercial, public sercice and military wireless networks currently. In outdoor applications, GPS is widely used, which can provide reliable position accuracy in the order of 3 to 10 m and is sufficient for many application. However, GPS typically perform poorly in indoor enviroments due to the signal attenuation and reflection introduced by buildings, walls and other structures. In addition, high positioning accuracy is required in some cases, such as industrial automation, patient monitoring and warehouse management.

Most of the current research methods for indoor positioning are based on single positioning technologies, such as RFID, WIFI, ZigBee and SINS [1-4]. However, these single positioning technologies have limitations. For example, RFID technology has the disadvantage of a low transmission power, small coverage area, low positioning accuracy and possible detection failures under high speed conditions. WIFI and ZigBee positioning technologies, based on the RSSI positioning mode, are easily affected by the environment and its positioning accuracy requires improvement. Inertial navigation devices integrate some inertial components, so have inherent accumulative error and positional excursion, and are not suitable for high working times [5].

As a type of single cycle pulse with benefits such as an extremely short duration, higher time resolution, strong penetrability, low transmission power and high data transmission rate [6-10], UWB is suitable for indoor positioning. However, the tracking trajectory of moving target would be distorted under the influence of multipath effect and NLOS factors. To improve positioning accurate, cooperative navigation system based on UWB and SINS is used. SISN can provide accurate position in a short time, detect and eliminate the influence of multipath effect and NLOS factors. At the same time, SISN can provide the real time velocity and accurate attitude information. In this regard, some scholars have carried out related researches and put forward coupled location model [13-17]. On the basis of previous researches, this paper further analyzes UWB/INS tightly coupled model and optimizes the system hardware parameters. PC is used to obtain and preprocess data from UWB and INS. Data will be fused through Klaman filter and optimal solution will be feedback to correct tightly coupled system parameters. The aim is to eliminate the influence from multipath and NLOS factors, improving the indoor positioning accuracy.

2 System model construction

The raw sensor measurements from the sensing components such as accelerpmeter, gyroscope and TDOA measurements are directly used for sensor fusion, instead of already filtered output quantities like position or acceleration. The data coupling mode can not only maximize the use of effective information in the case of UWB wireless sensors failure, but also deal with TDOA outliers occured regularly due to multipath effects and NLOS conditions. Additionally, the available inertial information gives accurate predictions of the UWB measurements. Hence, UWB/INS tightly coupled system possess long-term stability. Tightly coupled model is illustrated by Fig.1. The system consists of UWB wireless location unit, IMU inertial measurement unit and comprehensive data processing unit.

UWB wireless positioning unit consists of UWB signal generator and receiving base stations, finishing UWB signal generating, transmiting and received overall process. TDOA technology is used to measure the distance between moving target to be measured and reference nodes. IMU inertial measurement unit includes gyro, accelerometer and magnetometer, providing real-time angular velocity and linear acceleration for INS. Comprehensive data processing unit will get TDOA values, correct and compensate angular velocity and linear acceleration measured by INS, and it will carry on Kalman filtering and navigation solution. Moreover, the error compensation parameters can be real-time corrected.

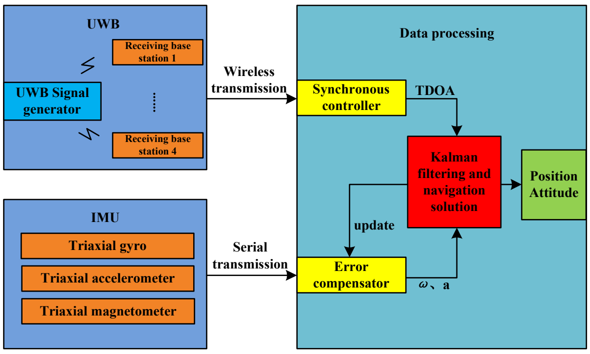

Fig. 1: UWB/INS tightly coupled model

2.1 UWB wireless system

TDOA technology is used to estimate position in UWB wireless system [18], as shown in Fig 2.

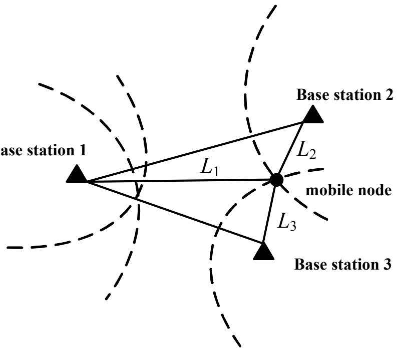

Fig. 2: Node positioning model of Ultra-wideband

The position of base stations has been fixed and the clocks have been synchronized in this system. Base station accepts UWB signals and transport the arrival time to central server, which can calculate time difference of arrival $t_{r,n}$ between anchor station and reference station:

$$t_{r,n} = t_r - t_n \tag{1}$$

Where t_r is the clock signal of the reference station, t_n is the clock signal of the known Nth base station. Hence, the distance between the target to be measured and the two base stations is:

$$L_{r,n} = ct_{r,n} = \sqrt{(x_k - x_r)^2 + (y_k - y_r)^2} - \sqrt{(x_k - x_n)^2 + (y_k - y_n)^2} \quad (2)$$

Where c is the speed of light, (x_k, y_k) is the coordinate of target to be measured, (x_n, y_n) is the coordinate of Nth base station, (x_r, y_r) is the coordinate of the reference station.

2.2 Inertial Navigation System

Inertial Navigation System (INS) can be divided into Inertial Measurement Unit (IMU) and Navigation Solution Unit (NSU). Where, IMU includes triaxial gyro, triaxial accelerometer and triaxial magnetometer, which are all after temperature compensation. The magnetometer can provide initial alignment and dynamic attitude angle compensation for gyro [19-20]. It is schematically presented in Fig 3.

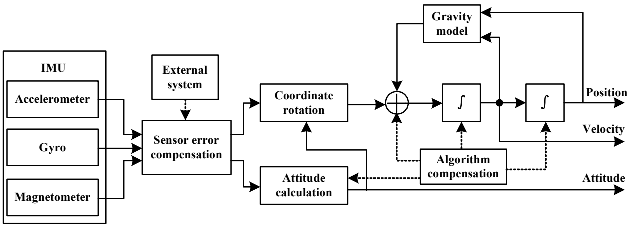

Fig. 3: Model of Inertial Navigation System

Inertial navigation system equations describe the propagation of the navigational states X_k (position, velocity and attitude in three dimensions) over time:

$$X_{k+1} = f_{ins}\left(X_k, U_k\right) + N_k \quad (3)$$

Where, N_k represents the deviation of the INS mechanization equations f_{ins} from the ideal kinematic equations as well as the imperfections of the gravity model. U_k is the IMU measured value, which is composed of the true values, a low-frequency noise component and a white noise term. In fact, INS can achieve accurate position and attitude in a short time.

3 Algorithm Design

3.1 Data preprocessing

In indoor enviroments wireless signal outage and severe multipath propagation very often lead to ranging errors and make pure UWB-based localization barely possible. Therefore, a method has been used to detect and correct the TDOA measurements. The coordinates of the two base stations involved are set to P_1 and P_2. $L_{1,2}$ is TDOA measurement value. The following inequality should be satistied according to the triangle theorem:

$$\left|L_{1,2}\right| \le \left\|P_1 - P_2\right\| - C \quad (4)$$

Where C is a constant, which can be set according to the true condition. Due to TDOA technology and hyperbolic principle, location errors are more likely to appear when the label is close to the nodes. Hence, the exclusion of the error measurements will improve the location accuracy of the tighyly coupled system.

3.2 Klaman filtering

In the inertia system, attitude calculation is relatively accurate because of the existence of magnetometer and gyroscope. The main error of INS is the accumulation of errors in each time. Therefore we just consider the navigation information for the mobile robot in the relative coordinate.

(1) System state equation

Klaman filtering takes INS position deviation and velocity deviation as state quantity in this tightly coupled positioning system.State equation is as follows:

$$\underbrace{\begin{bmatrix} \delta P_E(k) \\ \delta P_N(k) \\ \delta V_E(k) \\ \delta V_N(k) \end{bmatrix}}_{X_k} = \underbrace{\begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \delta P_E(k-1) \\ \delta P_N(k-1) \\ \delta V_E(k-1) \\ \delta V_N(k-1) \end{bmatrix}}_{X_{k-1}} + \underbrace{\begin{bmatrix} W_{PE}(k) \\ W_{PN}(k) \\ W_{VE}(k) \\ W_{VN}(k) \end{bmatrix}}_{W_k} \quad (5)$$

Where, $\left(\delta P_E(k), \delta P_N(k)\right)$, $\left(\delta V_E(k), \delta V_N(k)\right)$ are the errors of position and velocity measured by INS in east and north direction. T is sample time and W_k is the process noise vector with covariance Q.

(2) System measurement equation

The observation vectors of the filter are formed by difference of the UWB and INS position and velocities. Observation equation is as follows:

$$\underbrace{\begin{bmatrix}\Delta P_E\\ \Delta P_N\\ \Delta V_E\\ \Delta V_N\end{bmatrix}}_{\mathbf{Z_k}} = \underbrace{\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}}_{\mathbf{H}}\underbrace{\begin{bmatrix}\delta P_E(k)\\ \delta P_N(k)\\ \delta V_E(k)\\ \delta V_N(k)\end{bmatrix}}_{\mathbf{X_k}}+\underbrace{\begin{bmatrix}V_{PE}(K)\\ V_{PN}(K)\\ V_{PE}(K)\\ V_{PN}(K)\end{bmatrix}}_{\mathbf{V_k}} \qquad (6)$$

$$\Delta P = P_{ins} - P_{uwb}, \Delta V = V_{ins} - V_{uwb} \qquad (7)$$

Where, ΔP_E and ΔP_N are the position difference in east and north direction, respectively, ΔV_E and ΔV_N are the velocity difference in east and north direction. H is the measurement matrix of the Kalman filtering, V_k is the Gaussian process noise with covariance R.

4 Test and performance analysis of combined positioning system

4.1 Experimental research

The experimental environment in Figure 4 is set in order to verify the performances of the combined positioning system based on UWB and INS. The main devices in this test include one mobile robot (to simulate the moving target), four UWB positioning base-stations, one UWB wireless synchronous controller, one INS module, one upper computer and one positional tag. During the test, the refresh rate of the mobile nodes is 50Hz; and the UWB wireless signals received by the positioning base-stations from the positioning tag are used to further resolve the position by the upper computer.

Fig. 4: Experiment platform of of the combined positioning system

4.2 Experimental result and analysis

Figure 5 and 6 are the static trajectories of the combined positioning system, and the static position set in the experiment is (3.5, 2). The following results can be obtained based on the data analysis. The eastbound static positioning error range is (-0.04, 0.07); the average residual rate is 0.0034 and the confidence is 99.66%. The northbound static positioning error range is (-0.07, 0.09); the average residual rate is 0.0052 and the confidence is 99.48%.

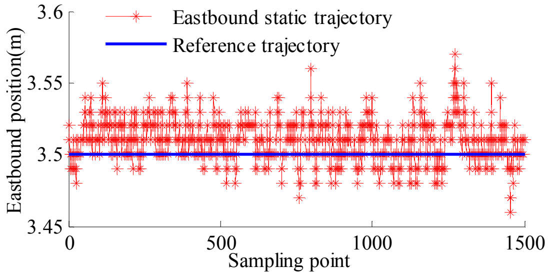

Fig. 5: Eastbound static trajectory

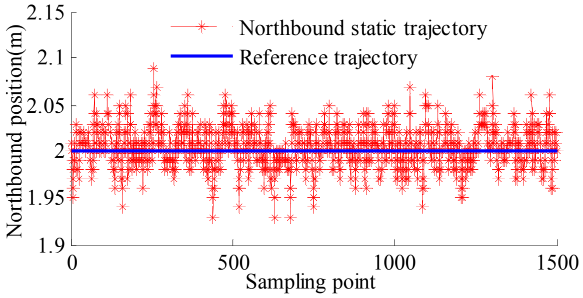

Fig. 6: Northbound static trajectory

The dynamic trajectory of the combined system obtained from the experiment is shown in Fig 7. The mobile robot moved at a constant velocity of 0.3m/s from point (2, 1) with a broken line form trajectory, passing through Point (3, 1), (3, 2), (4, 2) and (4, 3)and finally reaching Point (5, 3). The error between the trajectory and the referenced trajectory measured from the combined system is shown in Figure 8. which shows a trajectory error range of (-0.21, 0.16); average residual rate of 0.0078 and confidence is 99.22%.

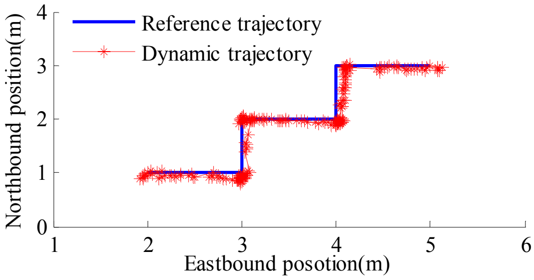

Fig. 7: Combined positioning trajectory

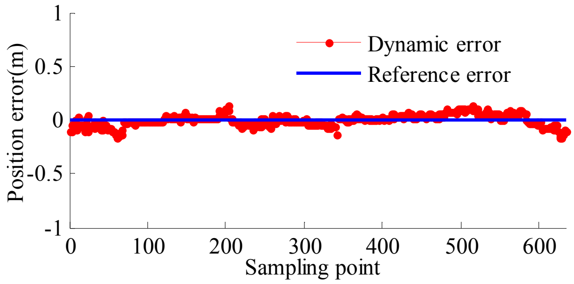

Fig. 8: Trajectory error of the combined positioning system

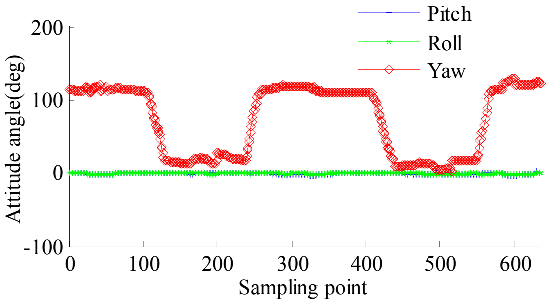

Fig. 9: Attitude angle trajectory of combined positioning system

Figure 9 is the attitude angle trajectory in the combined positioning experiment, which shows that the yaw angle changed 4 times during movement, while the pitch angle and roll angle remained steady without large changes. This is because the moving robot walked horizontally which only changed the yaw angle each time there was a node diversion. Hence, the experimental results meet the requirements.

5 Conclusions

In this paper, a tightly coupled indoor positioning system which uses the advantages of both UWB wireless positioning and INS is studied. By using a Kalman filter for data fusion and solving the problems of gyro drift and accelerometer 0 bias using INS, the system positioning accuracy is greatly enhanced.In the experiment, the static position errors of tightly coupled system is less than 0.1m and the confidence is more than 99.4%; the dynamic position errors is less than 0.25m and the confidence is more than 99%. Experimental results show that a tightly coupled positioning system based on UWB and INS has the benefits of high accuracy and good instantaneity, and can meet the requirements of indoor positioning applications.

Acknowledgments

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