A Novel Indoor Positioning Algorithm Based on IMU

Bi He[1], Hui Wang[1(✉)], Minshuo Li[1], Kozyrev Yury[1], and Xu Shi[2]

[1] School of Mathematics and Computer Science,
Zhejiang Normal University, Jinhua 321004, China
`hwang@zjnu.cn`

[2] School of Physics and Electronic Information Engineering,
Zhejiang Normal University, Jinhua 321004, China

Abstract. Although the Global Positioning System (GPS) can provide more accurate outdoor positioning services, it cannot detect the signals in indoor environments or in densely populated areas. Therefore, indoor positioning service has gradually been paid more attention. Most researchers currently use a nine-axis inertial sensor for indoor positioning. However, when the object is moving fast and frequently, it is obvious that using nine-axis inertial sensor has a large amount of computation. In addition, Kalman filtering algorithm is always cumbersome when data fusion is carried out for inertial sensors. The use of zero-velocity update algorithm (ZVU) to improve double integral can reduce the cumulative error, but the degree is far from enough. This paper mainly completes the following works: Firstly, the six-axis inertial sensor is used for indoor positioning. Then the digital motion processor is used instead of Kalman filter for attitude solution. Lastly, ZVU is optimized. Specifically, in the six-axis inertial sensor, the three-axis accelerometer is used to measure the force of the object, and the three-axis gyroscope is used to detect the current posture of the object. Since the three-axis magnetometer is missing, it is possible to effectively reduce a part of the calculation amount. In addition, the digital motion processor is used instead of the Kalman filter for the attitude solution, which avoids cumbersome filtering and data fusion. Finally, we optimize the ZVU so that the cumulative error is reduced again. The experimental results show that the algorithm proposed in this paper has certain feasibility and practical application value.

Keywords: Inertial sensor · Indoor positioning · Accelerometer · Gyroscope · Zero-velocity update

1 Introduction

Recently, with the continuous development of wireless sensor networks (WSNs), intelligent embedded systems and ubiquitous computing technologies, the demand

---

Foundation item: Natural Science Foundation of Zhejiang Province, China (No. LY16F020005).

H. Gao et al. (Eds.): ChinaCom 2019, LNICST 313, pp. 168–179, 2020.
https://doi.org/10.1007/978-3-030-41117-6_14

for location services has increased. Although the Global Positioning System (GPS) can provide more accurate outdoor positioning services, it cannot detect the signals in indoor environments or in densely populated areas. Therefore, indoor positioning service has gradually been paid more attention. Indoor positioning refers to the positional positioning in the indoor environment. It mainly integrates various technologies such as wireless communication, base station positioning, and inertial navigation positioning to form an indoor position positioning system, thereby realizing the position monitoring of people and objects in the indoor space.

For indoor positioning technology, the more mature indoor positioning systems are Active Badge [1], LANDMARC [2], Horus [3], AH-Los [4] and so on. In China, the research on this aspect started late, but also achieved some results. For example, the Weyes system of Beihang University [5], and the high-precision indoor positioning achieved by Ultra Wide Band (UWB) by the University of Science and Technology of China [6]. Generally, the above indoor positioning solutions can be classified into the following five categories according to the types of hardware devices: base station based technology, WIFI based technology, wireless sensor based technology, UWB based technology and inertial sensor based technology. Wherein, the base station based technology depends on the base station signal, and the positioning accuracy is low. The indoor positioning method based on WIFI, wireless sensor and UWB has high precision but high cost and is susceptible to the external interference. However, the inertial sensor based positioning technology does not depend on any external information, with good concealment and no external interference. Therefore, this paper adopts the inertial sensor based positioning technology.

So far, researchers have proposed a variety of indoor positioning methods based on inertial sensors, which are mainly divided into two types. One method is to estimate position based on approximate step size and step number. It estimates step size by acceleration and calculates step number to obtain position information. We call this method pedometer method (PM). Although this method avoids the increase of position error caused by double integral of acceleration, its accuracy may be limited by the influence of step size. Another method is based on inertial navigation theory, which estimates the position by transforming coordinate system and calculating double integral of acceleration. We call this method double integral method (DIM). Since the double integral method can pursue higher accuracy, this paper uses the double integral method based on inertial sensor to conduct indoor positioning.

However, most researchers currently use nine-axis inertial sensors for indoor positioning. The nine axes include three-axis accelerometers, three-axis gyroscopes and three-axis magnetometers. When the object is moving fast and frequently, it is obvious that using nine-axis inertial sensor has a large amount of computation. In addition, Kalman filtering algorithm is always cumbersome and computationally intensive when data fusion is carried out for inertial sensors. The usage of zero-velocity update algorithm (ZVU) to improve double integral can reduce the cumulative error, but the degree is far from enough. Therefore, how to reduce the computational complexity of indoor positioning based on inertial sensors and how to reduce the cumulative error caused by double integral method become the key issues of indoor positioning based on inertial sensors.

Therefore, in order to solve the above problem, we use a six-axis inertial sensor for indoor positioning. The six axes include a three-axis accelerometer and a three-axis gyroscope. We also used digital motion processor instead of Kalman filter for attitude solution. In particular, we calibrate the acceleration before using ZVU to further reduce the cumulative error. The main contributions of this paper are summarized as follows:

1. A six-axis inertial sensor is used for indoor positioning. The three-axis accelerometer is used to measure the force of the object, and the three-axis gyroscope is used to detect the current posture of the object. The lack of a three-axis magnetometer can effectively reduce the amount of computation and speed up the reaction when the object moves rapidly and frequently.
2. Based on six-axis inertial sensor, digital motion processor is used instead of the Kalman filter for attitude solution. It can appropriately reduce the workload of the processor and avoid cumbersome filtering and data fusion. In addition, the ZVU is optimized in this paper to reduce the cumulative error again.
3. Finally, based on the indoor positioning algorithm of inertial sensors, a simulation platform is built to verify the algorithm. The experimental results show that the algorithm is feasible and has practical application value.

The structure of the rest of this paper is as follows: in Sect. 2, the working principle of inertial sensor is briefly described, and the accelerometer and gyroscope are introduced respectively. In Sect. 3, the indoor positioning algorithm based on inertial sensor is introduced in details. In Sect. 4, the simulation platform is built for the indoor positioning algorithm described in this paper, and the experimental results are described. In Sect. 5, the full text is summarized.

2 Working Principle of Inertial Sensor

2.1 Accelerometer

The acceleration sensor is to use the inertia force produced by the motion of the object to obtain the acceleration of the object at the current moment. The acceleration sensor is mainly composed of three parts: a mass, an elastic component and a sensitive component. When an object moves, a force is exerted on the mass in one direction. At the same time, the elastic component deforms to a certain extent. The other end of the elastic component is the sensitive component. The sensitive component will detect the current acceleration according to the degree of deformation of the elastic component, so as to complete the acceleration detection [7]. The specific details are shown in Fig. 1, which shows the internal structure of single-axis acceleration sensor. As for the indoor positioning, the three-axis acceleration sensor is basically used. The three axes of the three-axis accelerometer are x, y and z axes respectively. Each coordinate axis direction contains a single-axis accelerometer as shown in Fig. 1. The accelerometer is used to measure the acceleration data in each direction. Its unit is m/s^2. It can be expressed as an acceleration vector. When the object is stationary, it returns the acceleration of gravity, so the acceleration sensor is also called the gravity sensor [8].

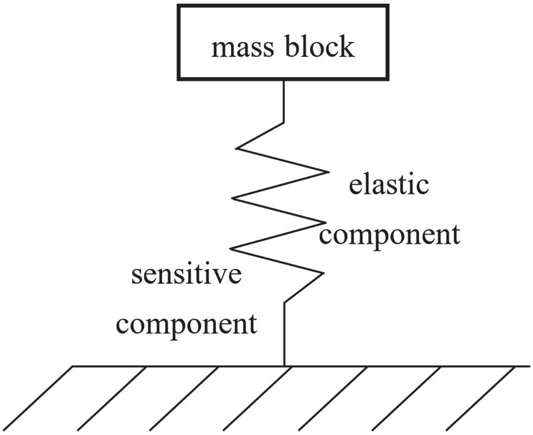

Fig. 1. Internal structure of single-axis acceleration sensor.

2.2 Gyroscope

Traditional mechanical gyroscopes, such as liquid floated gyroscope and electrostatic gyroscope, have high-velocity rotating rotors inside. It uses the mechanical characteristics of gyroscope to measure the angle with high accuracy. Optical gyroscopes, such as laser gyroscopes and fiber optic gyroscopes, use the Sagnac effect of light propagation to calculate the angular velocity of rotation. In this paper, we use a MEMS gyroscope, which is also a mechanical gyroscope. Its working principle is different from these two types of gyroscopes. In particular, the MEMS gyroscope is small in size, and it is difficult to design a gyro rotor with a large moment of inertia and to detect the mechanical properties of the rotor. Therefore, the MEMS gyroscope of the vibration type structure is basically used. It calculates the angular velocity by measuring the Gothic acceleration acting on the vibration components. The specific details are shown in Fig. 2, which shows the internal structure of a single-axis MEMS gyroscope. In the indoor positioning, a three-axis gyroscope sensor is basically used. The three axes of the three-axis gyroscope sensor are x, y and z axes respectively. Each coordinate axis direction contains one of the above single-axis gyroscope sensor. It is used to measure the gyroscope data in each direction. Its unit is rad/s. When a three-axis MEMS gyroscope works, its internal vibration mass block will vibrate in accordance with a certain driving mode. If an axis of the gyroscope generates angular velocity, the angular velocity will be calculated by detecting the Gothic force acting on the vibration mass block [9].

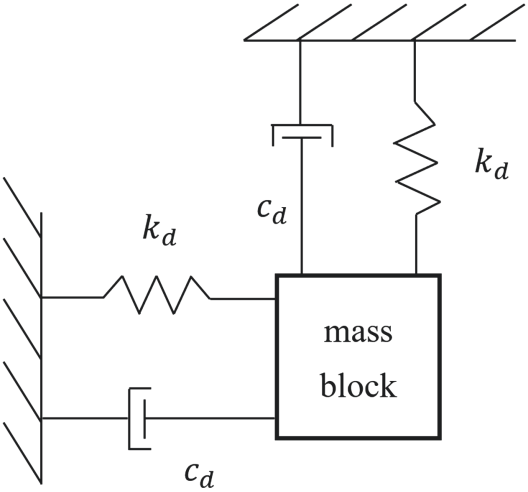

Fig. 2. Internal structure of single-axis gyroscope sensor.

3 Indoor Positioning Algorithm of Inertial Sensor

This paper proposes an indoor positioning algorithm based on inertial measurement unit (IMU). The block diagram of the indoor positioning algorithm is shown in Fig. 3. The upper, middle and lower portions of the figure correspond to four main components of the algorithm, with the lower part of the figure covering two parts. The upper part of the figure describes the algorithm of solving quaternion by digital motion processor (DMP). It is used to directly calculate quaternion q from acceleration measurement value a_b and gyroscope measurement value $gyro_b$. The middle part of the figure describes the coordinate transformation algorithm. It transforms the acceleration measurement a_b of the carrier coordinate system into the acceleration measurement value a_n of the geographic coordinate system by the quaternion q obtained by the DMP solution quaternion algorithm. The lower part of the figure describes the acceleration double integral algorithm and the zero-velocity update algorithm (ZVU). The ZVU algorithm is used in the acceleration double integral algorithm, so they are placed together. The output of this part includes the velocity estimate v and the position estimate p. Each component of the indoor positioning algorithm will be described in details in the following sections.

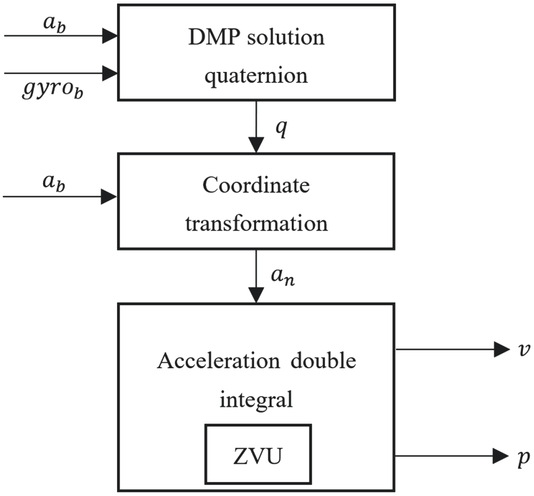

Fig. 3. Block diagram of indoor positioning algorithm.

3.1 DMP Solution Quaternion

The MPU6050 integrates an extensible digital motion processor (DMP). DMP is the unique hardware feature of InvenSense MPU devices. It combines the data of accelerometer and gyroscope, and directly solves the quaternion from it. It can reduce the workload of the main processor, avoid cumbersome filtering and data fusion processing, and reduce the complexity of system operation. Moreover, the main processor only needs to read the data when the DMP processing is completed. During DMP processing, the main processor can handle other tasks. This can improve the efficiency of the processor. In addition, the DMP images are stored on the non-permanent memory of the main processor, and the set data will disappear after power off. Therefore, every time the DMP function is activated on power, it is necessary to initialize the DMP. The flow chart of DMP solution quaternion is shown in Fig. 4:

3.2 Coordinate Transformation

Since the coordinate system of the chip is different from the coordinate system of the object, the sensor data should be transformed between the two coordinate systems. The coordinate systems involved are explained as follows:

1. Geographical Coordinate System
   Commonly used geographic coordinate systems mainly include the "East-North-Sky" coordinate system and the "North-East-Earth" coordinate system. This article uses the "East-North-Sky" coordinate system, also known as the Inertial Cartesian coordinate system. The origin is the center of mass of the carrier, the x axis points east along the direction of the local latitude,

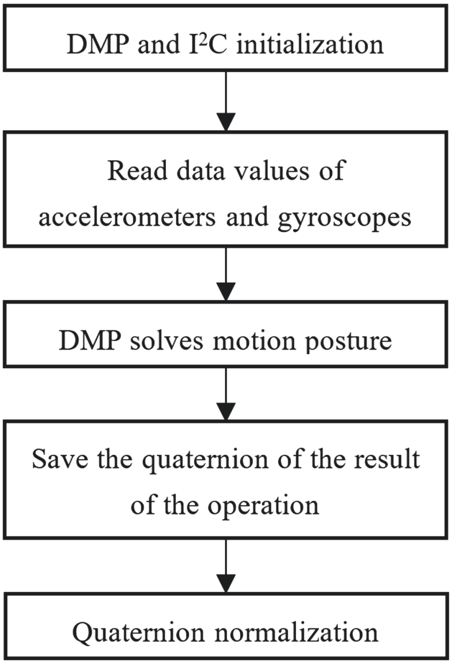

Fig. 4. Flow chart of DMP solution quaternion.

the y axis points north along the direction of the local meridian, and the z axis is determined by the right-hand rule. The geographic coordinate system is usually indicated by the lower corner "n".

2. Carrier Coordinate System
   The carrier coordinate system in this paper is the coordinate system of a certain part of the moving object carrying the inertial measurement unit (IMU). It will change with the movement of the object. The carrier coordinate system is self-defined. It consists of three axes that are orthogonal to each other. The origin of the coordinate system is usually set to the position of the center of gravity of the moving object. The x-axis is directed in the direction of moving forward, the y-axis is perpendicular to the direction of gravity acceleration, and the z-axis is perpendicular to the xoy plane. It follows the right-hand rule. The carrier coordinate system is usually indicated by the lower corner "b".

In the process of moving, the position change of the object is directed at the geographic coordinate system, which reflects the navigation information. The sensor data is relative to the chip itself, i.e. the carrier coordinate system, which reflects the posture information. In order to estimate the position of the object in the geographic coordinate system using the sensor data in the carrier coordinate system, coordinate transformation is needed.

There are many ways to coordinate transformation. In this paper, the quaternion method is used. Specifically, the geographic coordinate system is $ox_ny_nz_n$, and the carrier coordinate system is $ox_by_bz_b$. When the object moves, the measured value in the carrier coordinate system is $a_b(t) = (a_{bx}(t), a_{by}(t), a_{bz}(t))$. After coordinate conversion, the value in the geographic coordinate system is $a_n(t) = (a_{nx}(t), a_{ny}(t), a_{nz}(t))$. The conversion relationship is as follows:

$$a_n(t) = q_m(t) \otimes a_b(t) \otimes q_m^*(t). \tag{1}$$

Among them, $q_m(t)$ is the quaternion at time t obtained by the DMP solution in the previous section. $q_m^*(t)$ is the conjugate quaternion of $q_m(t)$, and $\otimes$ represents the quaternion multiplication. Acceleration vectors $a_b(t)$ and $a_n(t)$ are regarded as pure vector quaternions. When multiplying quaternions, its scalar part is equal to zero.

3.3 Acceleration Double Integral

Through the coordinate transformation of the above section, we can get the acceleration vector $a_n(t)$ of the geographic coordinate system. By subtracting the gravity acceleration $g_n(t)$ from $a_n(t)$, we obtain the acceleration driven by the motion as follows

$$a_n^m(t) = a_n(t) - g_n(t). \tag{2}$$

According to Newton's basic law of inertia, the instantaneous velocity is obtained by integrating the acceleration of the object. The acceleration of the object is double integral and the position of the object is obtained. When the object moves continuously from time 0 to time t, the sampling time is t. The distance is set as $p_n^m(t)$. The instantaneous velocity is set to $v_n^m(t)$, and the acceleration value measured by the accelerometer is $a_n^m(t)$. The relationships between the three are as follows:

$$v_n^m(t) = \int_0^t a_n^m(\tau)\mathrm{d}\tau, \tag{3}$$

$$p_n^m(t) = \int_0^t v_n^m(\tau)\mathrm{d}\tau. \tag{4}$$

Therefore, in the geographic coordinate system, the result of formula (2) is used to integrate the acceleration $a_n^m(t)$ to obtain the three-dimensional velocity vector $v_n^m(t)$. Then, the three-dimensional velocity vector $v_n^m(t)$ is integrated to obtain the position information $p_n^m(t)$.

3.4 Zero-Velocity Update Algorithm

The above method is feasible under the ideal conditions. However, the measured acceleration vector $a_n^m(t)$ has the noise and the drifted errors. If the velocity vector $v_n^m(t)$ is immediately integrated, the position estimation error will be infinitely amplified. The zero-velocity update algorithm (ZVU) came into being.

ZVU is an algorithm that reduces the position estimation error. Its basic idea is that at the beginning and end of the movement, the ideal velocity is zero. If the actual measured velocity is not zero, forcibly set it to zero. The difference between the actual velocity (known as zero) and the velocity obtained by integrating the acceleration is used to correct the acceleration offset error, thereby reducing the position estimation error. The derivation process of the zero-velocity update algorithm is as follows:

$$a_n^m(t) = a_n^a(t) + \varepsilon, t \in [0, T], \tag{5}$$

$$v_n^m(t) = \int_0^t a_n^m(\tau)\mathrm{d}\tau = \int_0^t [a_n^a(\tau) + \varepsilon]\mathrm{d}\tau = \int_0^t a_n^a(\tau)\mathrm{d}\tau + \int_0^t \varepsilon\mathrm{d}\tau = v_n^a(t) + \varepsilon t, \tag{6}$$

$$\varepsilon = \frac{v_n^m(T)}{T}. \tag{7}$$

In the above derivation process, the motion-driven acceleration $a_n^m(t)$ is divided into two parts. $a_n^a(t)$ is the actual acceleration vector. ε is the acceleration offset error. T is a period of the object motion. In a period, ε is considered to be a constant. The initial velocity of a moving object is zero, so the derivation (6) of velocity vector $v_n^m(t)$ can be obtained by substituting formula (5) into formula (3). Among them, $v_n^a(t)$ is the actual velocity vector, and εt is the velocity error caused by acceleration bias error. When the motion of the object ends, i.e. $t = T$, the actual velocity $v_n^a(T)$ is zero. Substituting it into the formula (6), the formula (7) can be obtained. That is, the acceleration bias error ε is obtained. From ε, the position estimation error can be reduced. The optimization of ZVU in this paper is to calibrate the deviation of acceleration before ZVU, so as to improve the indoor positioning accuracy of the algorithm.

4 Simulation of Indoor Positioning Algorithm Based on IMU

In order to verify the effectiveness and positioning accuracy of IMU based on indoor positioning algorithm, this section gives the simulation results of the above algorithm, discusses and analyzes it. First, we collect the data of the MPU6050 six-axis sensor. Then, use the MATLAB simulation platform to analyze and process the collected data. Finally, simulate the zero-velocity update algorithm to verify the effectiveness of the algorithm and test the performance of the improved algorithm.

Among them, the MPU6050 six-axis sensor integrates three-axis accelerometer and three-axis gyroscope. The parameters are shown in the following Table 1.

4.1 Zero Correction Simulation

The z-axis of the chip is put up and stationary horizontally. Theoretically, the acceleration measurement value of x-axis and y-axis is 0 and the acceleration

Table 1. Parameter description.

Name	Parameter
Measurement dimension	Accelerometer: 3D; Gyroscope: 3D
Range	Accelerometer: 2g; Gyroscope: 2000dps

measurement value of z-axis is $9.8m/s^2$. However, this is not the case in actual measurement. The values of the x and y axes are not zero, and the value of the z axis is also deviated from $9.8m/s^2$. Figure 5 illustrates only the x-axis as an example. The dotted line represents the acceleration of the x-axis before correction and the solid line represents the acceleration of the x-axis after correction. It can be seen from the dotted line part of Fig. 5. When the sensor is placed horizontally with the z-axis facing upward and in a static state, the measured value of the x-axis acceleration is different from zero. Therefore, it is necessary to calibrate the deviation of the measure value of the sensor. That is, the offset is calculated first and compensated then. The corrected measurements are shown on the solid line of Fig. 5. Compared with the dotted line part of Fig. 5, the acceleration value of the x-axis tends to zero in the static state. By this design, the velocity and position can be obtained more accurately when the acceleration is integrated subsequently.

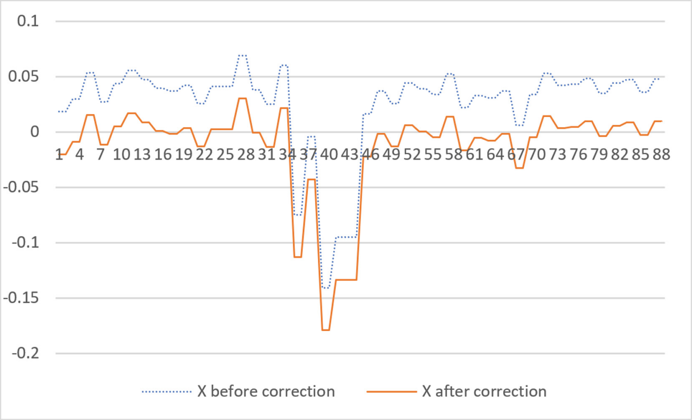

Fig. 5. Comparison of x-axis acceleration before and after correction.

4.2 Zero-Velocity Update Simulation

Similar to the last section, we take the x-axis as an example to illustrate the simulation experiment. Firstly, we assume that if the zero-velocity update algorithm is not adopted, the acceleration can be directly integrated to obtain the uncorrected velocity curve. The dotted line is shown in Fig. 6, where the horizontal axis represents the sampling time, and the vertical axis represents the velocity on the x axis. The unit is m/s. According to the dotted line in Fig. 6, the velocity after the motion is not zero due to the error caused by the integral. On the contrary, if the zero-velocity update algorithm is adopted, we re-integrate the acceleration to obtain the corrected velocity curve, as shown on the solid line in Fig. 6. Obviously, it can be seen from the solid line in Fig. 6 that the velocity at the end of the movement is close to zero after the correction of the zero-velocity update algorithm. Therefore, the zero-velocity update algorithm can effectively reduce the acceleration bias error.

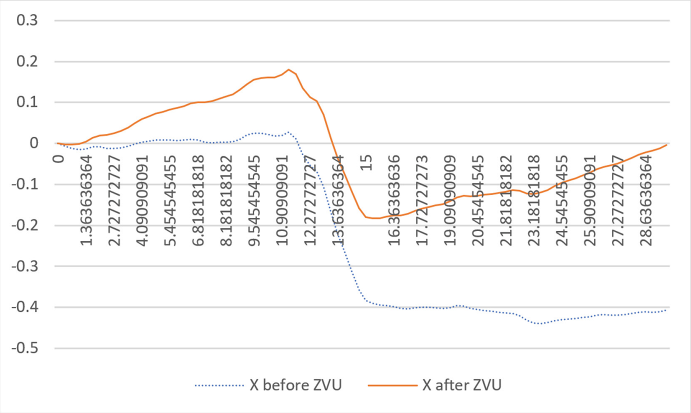

Fig. 6. Comparison of x-axis velocity before and after ZVU.

5 Conclusion

Aiming at the computational complexity and positioning accuracy of indoor positioning, this paper uses the six-axis inertial sensor, and designs the indoor positioning algorithm based on the six-axis inertial sensor. The algorithm includes digital motion processor, coordinate transformation, acceleration double integral and ZVU optimization. The digital motion processor replaces Kalman filter for attitude solution. Coordinate transformation is used for the transformation between geographic coordinate system and carrier coordinate system. The deviation calibration of acceleration before ZVU can make the positioning accuracy higher. The simulation results show that the algorithm has certain feasibility and practical application value.

References

1. Want, R., Hopper, A., Falcao, V., et al.: The active badge location system. ACM Trans. Inf. Syst. (TOIS) **10**(1), 91–102 (1992)
2. Ni, L.M., Liu, Y., Lau, Y.C., et al.: LANDMARC: indoor location sensing using active RFID. In: Proceedings of the First IEEE International Conference on Pervasive Computing and Communications, 2003, (PerCom 2003), pp. 407–415. IEEE (2003)
3. Youssef, M., Agrawala, A.: The horus WLAN location determination system. In: Proceedings of the 3rd International Conference on Mobile Systems, Applications, and Services, pp. 205–218. ACM (2005)
4. Savvides, A., Han, C.C., Strivastava, M.B.: Dynamic fine-grained localization in ad-hoc networks of sensors. In: Proceedings of the 7th Annual International Conference on Mobile Computing and Networking, pp. 166–179. ACM (2001)
5. Victor, L., Xu, K., Gu, C.: A difference model for open WLAN environment based location service. IEEE Infocom (2006, submitted)
6. Yanlong, Z.: Research on Key Technologies of Indoor Positioning. University of Science and Technology of China (2014)
7. Chunbin, G.: Research on indoor positioning technology based on mobile terminal sensor. University of Electronic Science and Technology of China (2015)
8. Hongli, S.: Research and implementation of indoor positioning system based on dead reckoning. University of Electronic Science and Technology of China (2018)
9. Qintuo, Z.: Research on positioning and orientation device based on MEMS inertial sensor. Harbin Engineering University (2008)