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Research Article

A Pedestrian Dead Reckoning System Integrating Low-Cost MEMS Inertial Sensors and GPS Receiver

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Abstract

The body-mounted inertial systems for pedestrian navigation do not require any preinstalled facilities and can run autonomously. The advantages over other technologies make it especially attractive for the applications such as first responders, military and consumer markets. The hardware platform integrating the low-cost, low-power and small-size MEMS (micro-electro-mechanical systems) inertial sensors and GPS (global positioning system) receiver is proposed. When the satellite signals are available, the location of the pedestrian is directly obtained from the GPS receiver. The inertial sensors are the complement of the GPS receiver in places where the GPS signals are not available, such as indoors, urban canyons and places under dense foliages. The height tracking is achieved by the barometer. The proposed PDR (pedestrian dead reckoning) algorithm is real-timely implemented in the platform. The simple but effective step detection and step length estimation method are realized to reduce the computation and memory requirements on the microprocessor. A complementary filter is proposed to fuse the data from the accelerometer, gyroscope and digital compass for decreasing the heading error, which is the main error source in positioning. The reliability and accuracy of the proposed system is verified by field pedestrian walking tests in outdoors and indoors. The positioning error is less than 4% of the total traveled distance. The results indicate that the pedestrian dead reckoning system is able to provide satisfactory tracking performance.

Keywords: Pedestrian Dead Reckoning, Inertial sensor, GPS, complementary filter, indoor navigation

1. Introduction

The pedestrian navigation system(PNS) provides walking velocity and position of a person, which can be applied in location based services(LBS), rescue, military infantry, science, tourism, sports, games, navigation aids for the blind or visually impaired man etc[1], [2]. A robust and accurate positioning system with seamless outdoor and indoor coverage is required[3]. The GPS provides position and velocity information and is widely applied in most open environments[4], [5]. When the GPS signals are available, the absolute position with a few meter error can be attained. However, due to the satellite signal degradation and interference, the GPS signal is not reliable enough to produce good position information in deep street canyons and indoor environments where most pedestrian travels take place[6]. It is necessary to develop a positioning system to overcome these limitations[7].

The positioning sensing techniques, such as ultra wide band (UWB), radio frequency identification (RFID), WLAN, Bluetooth(BT) techniques, are utilized to obtain a seamless indoor/outdoor positioning. But these systems require fix infrastructures. The operational environments encountered will be very diverse. The availability of such infrastructures cannot be guaranteed in all applications. A self-contained navigation system with wearable sensors based on the dead reckoning (DR) principle is preferable solution. It has the advantage that no preinstalled infrastructures and priori information are required. Once initialized, the system is completely autonomous[3]. The dead reckoning is a relative navigation technique using walking distance and heading. Starting from a known origin, the successive position displacements are added up to calculate the position of the PNS user[1], [8], [9].

The PNS must be low-cost, light-weight, small-size, low-power, easily mounted on the body and provides meter-level accuracy during operations[3], [10]. The MEMS inertial sensors are the pretty choice[6]. However, MEMS sensors exhibit small measurement errors which tend to accumulate into big positioning errors with time during the integral process[11]. Therefore, the suitable hardware and corresponding algorithms are required in order to provide the navigation information with acceptable accuracy in both outdoor and indoor environments[2], [9].

The PNS system integrating GPS receiver and self-contained MEMS inertial sensors is proposed in this paper to provide positioning capability for pedestrians. The inertial sensors, such as the accelerometer, gyroscope and magnetic compass, are included in the system. The barometer is

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introduced to improve the positioning availability and accuracy in the vertical direction. The proposed approach is to use the accelerometer to detect the step occurrence and estimate the step length. A complementary filter is utilized to fuse the sensor data to obtain high-precision heading information. The GPS signal is used to correct the heading errors measured from the MEMS sensors when it is reliable. The paper is organized as following. The hardware system and algorithm architecture are presented in section 2. The inertial sensor module is described in detail in section 3. The algorithms and software design are proposed in section 4. The results of experiment tests are shown to verify the performance of the proposed system in section 5. Finally, concludes are given in section 6.

2. System Overview

The hardware of the proposed PNS system is divided into four distinguishable parts: microprocessor, GPS receiver, inertial measure unit(IMU) and the notebook computer. The 32-bit microprocessor STM32F407 is the core part of the system, which acquires the signal of the sensors, GPS receiver and implements the algorithm online. The U-blox GPS receiver LEA-5 provides position estimation according to the UBX protocol. The IMU contains the Invensense 3-axis accelerometer and 3-axis gyroscope MPU6050, Honeywell 3-axis digital compass HMC5883 and Measurement Specialties barometric pressure sensor MS5611. The three inertial sensors are mounted in perpendicular directions in the PCB(printed circuit board). The notebook computer communicates with the microprocessor via UART interface to collect the data of the sensors and record the results of the position and heading. The hardware system diagram is shown in Fig. 1.

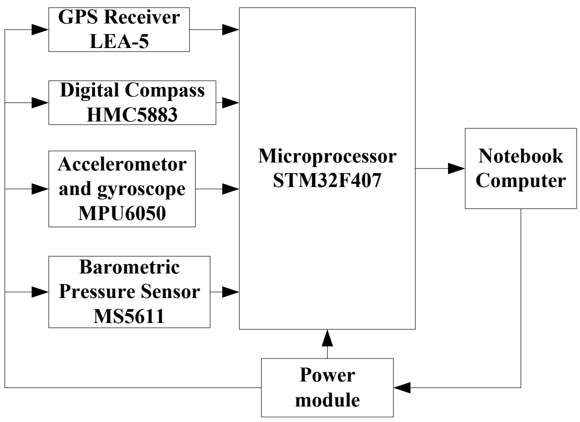

Fig. 1 The hardware system diagram of the proposed PDR system

The MEMS inertial sensors have the advantages of small size, light weight, low cost and low power consumption with long field testing capability, which make it a favourable option for commercial applications[3], [4]. The IMU with a dimension of 60 mm x 40 mm x 14 mm(length × width ×height), weighing only 32 g. The GPS receiver is integrated with the inertial sensors to determine the displacement of the pedestrians. When the GPS signal is not available, the navigation solution can only be obtained from the IMU based on the DR principle. When the GPS signal is reliable, it provides the position and altitude information of the pedestrians. The heading error from the inertial sensors is updated at the same time. The proposed PDR algorithm structure is shown in Fig. 2. The acceleration signal is analyzed to detect the step occurrences and compute the

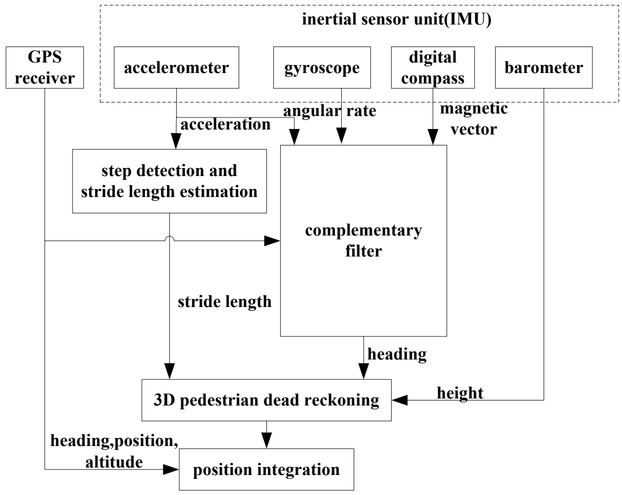

Fig. 2 The proposed algorithm structure

stride length which is integrated with the azimuth measured by the gyroscope and digital compass to calculate the position. The valid peaks of the acceleration correspond to the step occurrences. The acceleration signal is fed to a digital low-pass filter to cancel the double peak effects. The predefined threshold and time interval are utilized to observe the peaks. The time interval between the two successive valid peaks is step period, which is used to estimate the stride length. The MEMS inertial sensors have large noise contributions and bias drifts, which are especially prone to result in large heading error[3]. A complementary filter is introduced to overcome the limitation.

3. Hardware Design

The hardware circuit designs of the microprocessor, GPS receiver, inertial sensors including the accelerometer, gyroscope, digital compass and barometer are described in detail in the section.

3.1 Microprocessor

The microprocessor chip STM32f407 based on high performance ARM 32-bit Cortex™-M4 RISC is selected as the core chip of the hardware system. The external 8 MHz crystal oscillator is used, and the operating frequency is up to 168 MHz which is sufficient for the high-precision real-time data processing. It has 1M bytes of flash memory and 192k bytes of SRAM. The chip has multiple general-purpose timers and communication interfaces including three I2Cs, three SPIs and four USARTs. This is convenient to communicate with the peripheral circuits. The microprocessor real-timely collects and processes large amounts of data from the GPS receiver, accelerometer, gyroscope, digital compass and barometer to determine the position of pedestrians.

3.2 Accelerometer and Gyroscope

The InvenSense MPU6050 with embedded 3-axis MEMS accelerometer and gyroscope is chosen. The acceleration along a particular axis induces a displacement on the corresponding proof mass which is detected by the capacitive sensors and converted into a linear voltage signal.

The 16-bit sigma-delta ADC on each axis provides digital outputs. The full scale range of the acceleration can be adjusted to ±2*g*, ±4*g*, ±8*g*, or ±16*g*. When the gyroscope is rotated around the sense axis, the Coriolis force causes a vibration that is picked-up by the sensing capacitors and converted into a voltage proportional to the angular rate by the signal conditioning circuit. This voltage is digitized using on-chip 16-bit ADC. The full-scale range of the gyroscope can be programmed to ±250, ±500, ±1000, or ±2000 degrees per second. The MPU6050 supports the I2C protocol, the interface circuit is shown in Fig. 3.

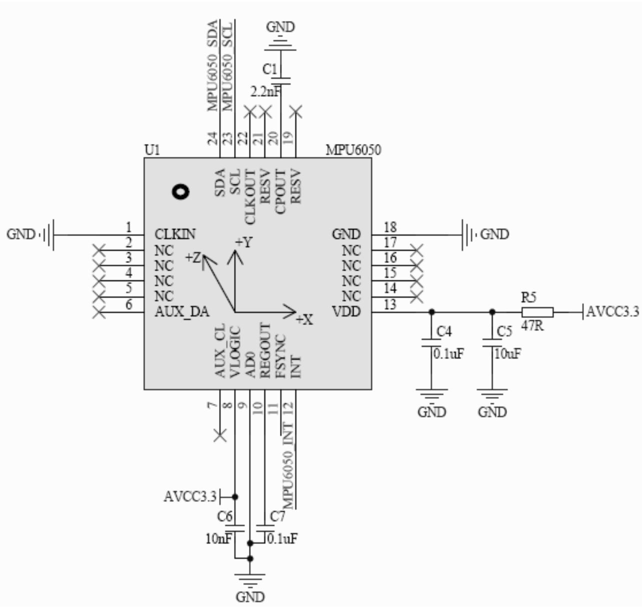

Fig. 3 The interface circuit of MPU6050

3.3 Digital Compass

To maintain the low weight of the system and gain the heading autonomously, the Honeywell 3-axis digital compass HMC5883L is selected for integrating into the system. It combines magneto-resistive sensors with an ASIC and a 12-bit ADC to obtain the heading accuracy from 1 to 2 degree. The full scale is ±8 *gauss*. The chip provides the I2C serial interface, and the circuit is shown in Fig. 4.

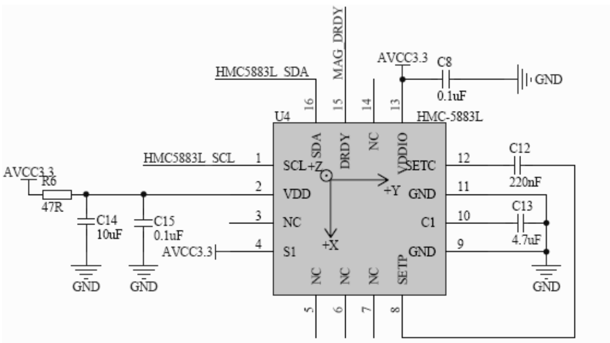

Fig.4 The interface circuit of HMC5883

3.4 Barometric Pressure Sensor

By integrating the Measurement Specialties MS5611 barometer, the system is able to calculate the altitude change over time. The floor the user located in can be estimated from the altitude information inside buildings. This opens possibilities for 3D positioning. The test range of the high-linearity pressure sensor is from 10 to 1200 mbar. A high-precision 24-bit sigma delta ADC is included. The over-sampling rate(OSR) of the ADC can be programmed to 256, 512, 1024, 2048 and 4096. The altitude resolution is 10 cm. To compensate the variations of the process and temperature, 6 internal factory calibrated coefficients are stored in the 128-bit PROM. The chip supports the I2C and SPI protocol, the interface circuit is shown in Fig. 5. Which protocol used is determined by the pin PS. Pulling pin PS to low selects the SPI protocol.

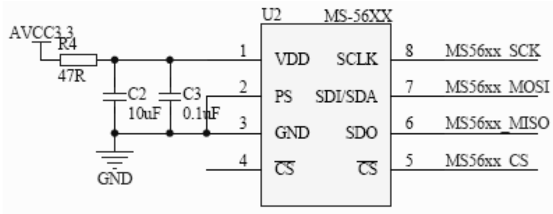

Fig. 5 The interface circuit of MS5611

3.5 LEA-5 GPS Receiver

The GPS is a satellite-based radio navigation system, which provides 3D absolute position. The horizontal position accuracy of the U-blox GPS receiver LEA-5 is less than 2.5 m. The configurable UART serial interface in the receiver is convenient to communicate with the core chip. The interface circuit is shown in Fig. 6.

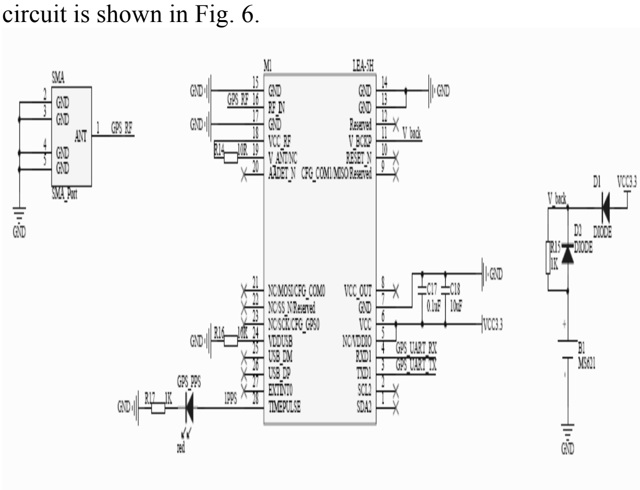

Fig. 6 The interface circuit of the GPS receiver

4. PDR Algorithm and Software Architecture

The GPS signal is integrated with the PDR to provide the position of the pedestrians in outdoors and indoors. The step detection, stride length estimation and heading calculation are three main aspects of the PDR.

4.1 Data Collection

The data of the 3-axis accelerometer and gyroscope MPU6050 are read from the registers of the embedded digital motion processor by the I2C interface. The write address is 0xd0, and the read address is 0xd1. The acceleration and rotation rate of x, y, z-axis are sequentially read starting from the ACCEL_XOUT_H register. The data of the 3-axis digital compass HMC5883 is read by I2C interface, which is similar to MPU6050. The write address is 0x3c, and the read address is 0x3d. The magnetic vectors of x, z and y-axis are sequentially read starting from the X_MSB register.

The pressure value from the barometer is affected by the process technology and temperature. Thus, 6 coefficients are stored in the PROM to calibrate the tested value. The initial program of the device includes initializing SPI port, resetting chip and reading the calibration coefficient. The compensated pressure value is obtained with the help of the temperature value and the coefficients. The relationship between the gas pressure and the altitude is:

$$P = P_0(1 - \frac{H}{44330})^{5.255} \tag{1}$$

Where

P_0 is the standard atmospheric pressure whose value is 1013.25 mbar

H is the height in meter

P is the atmospheric pressure the user located in mbar

The soft process is shown in Fig. 7.

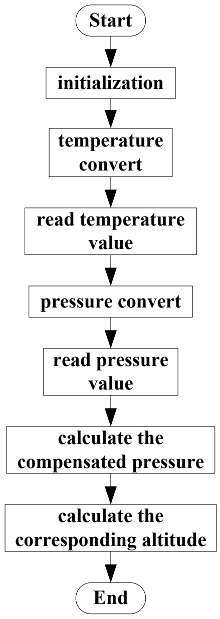

Fig. 7 The read process of MS5611

The GPS receiver LEA-5H uses UBX protocol to transmit the data, such as longitude, latitude and height, via a USART interface with a baud rate of 57600.

4.2 Step Occurrence Detection and Stride Length Estimation

An accurate and robust step occurrence detection algorithm is required for the PDR navigation system. The human physiological characteristic during a walk is cyclical. The horizontal velocity of a foot repeatedly varies from stationarity, acceleration, deceleration to stationarity again during every stride[12]. The step occurrence can be determined by a peak detection algorithm based on the data from the accelerometer. The total acceleration value obtained from the three orthogonal accelerometer signals is compared with the predefined thresholds, and the minimum step period is taken into account to identify the step occurrences[13]. The raw acceleration signal has multiple peaks in each stride due to the complicated walking dynamics. A low-pass filter is applied to smooth the signal due to the fact that the normal walking frequency of the pedestrian is less than 3 Hz[2]. The output of the filter is calculated by

$$\bar{a}_k = \frac{1}{L}\sum_{i=k-L+1}^{k} a_i \tag{2}$$

where

L is the width of the sliding window.

Then, the smoothed acceleration is evaluated whether it is a peak, and the magnitude is greater than the predefined threshold. Once the peak exceeds the threshold, and the time interval with the previous valid peak is greater than the predefined minimum, a new step is detected. The end point of the step is found by zero-crossing. A finite state machine structure is designed and the soft process is shown in Fig. 8.

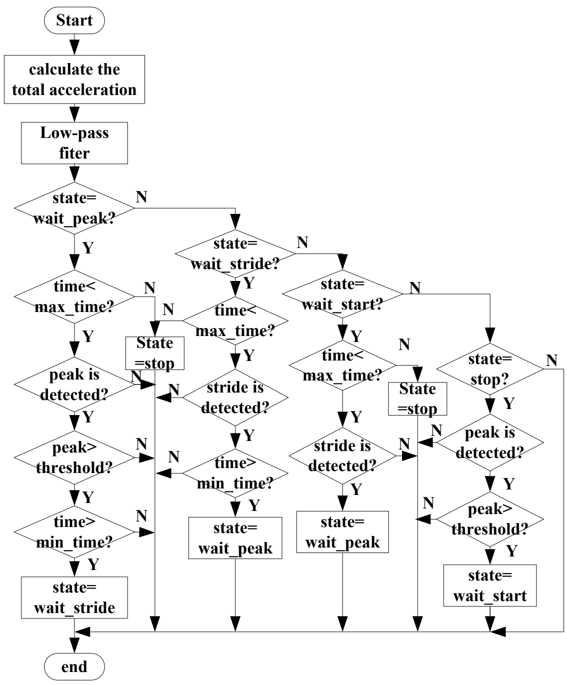

Fig. 8 The soft process of the step occurrence detection

The result of step detection is illustrated in Fig. 9. The total acceleration signals before and after filtering for 81 steps at normal walking speed are shown. The blue circles in (b) illustrate the valid peak detected in every step.

The step length is an important parameter in PDR. The step length is not a constant, but varies with time. It is inappropriate to fix an average step length for each specific user. The step size changes with the walking frequency of the user[10]. In typical human walking behaviour, the step length increases as the step frequency becomes quicker. The step length could be estimated based on a linear relationship with the measured step frequency[14]. When the step frequency is between 1.35 and 2.45, the linear relationship can be expressed as following[13]:

$$S = 0.4504f - 0.1656 \tag{3}$$

Where
f is the frequency
S is the stride length.

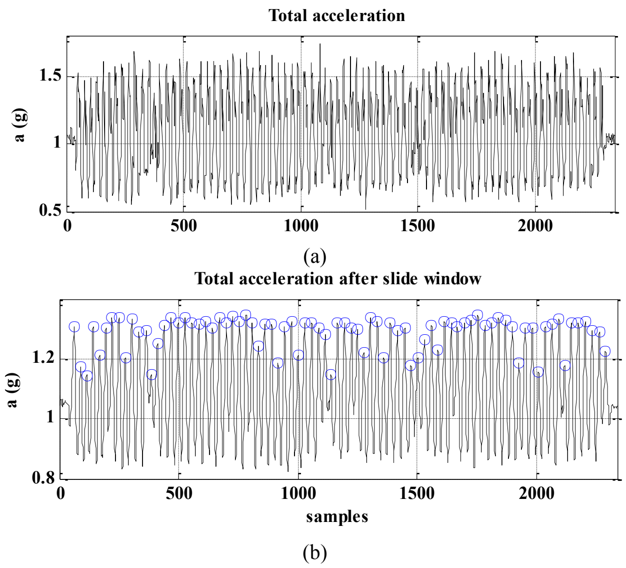

Fig. 9 step detection (a) total acceleration signal before filtering (b) after filtering

4.3 Azimuth Calculation

The azimuth is a key component in PDR. The small error of the azimuth will result in great deviation in the position. The high-precision azimuth can be obtained from the GPS receiver when the signal is available. In indoors, the digital compass can provide the azimuth information directly; however, the magnetic disturbance in the buildings, such as the elevator and the metallic fence of the stairs, contaminates the measurements of the digital compass and induces fatal error. The gyroscope can correct the magnetic disturbances. Nevertheless, the low-cost gyroscope is susceptible to drift errors which can be compensated by the compass[14]. A complementary filter is proposed to integrate the gyroscope and the digital compass for reliable azimuth of the pedestrians. The algorithm structure is shown in Fig. 10.

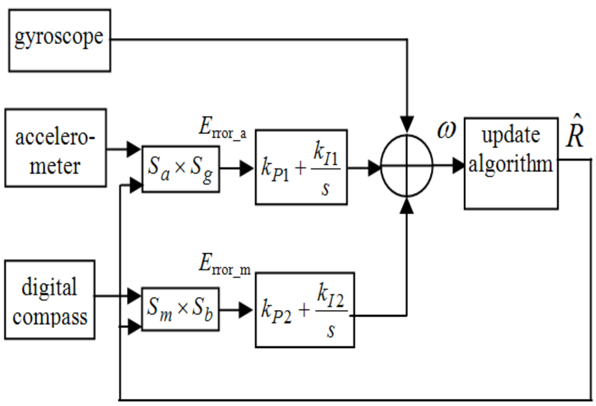

Fig. 10 The proposed algorithm structure of azimuth by complementary filter

In Fig. 10, S_a is the measurement acceleration from the x, y and z-axis, S_g is the predefined reference direction of the field in the sensor frame, S_m is the measurement magnetism from the x, y and z-axis, S_b is the reference direction of the magnetic field in the sensor frame. *E*rror_a and *E*rror_m are the error between the measured value and the reference value.

4.4 Position Determination

From a known point, the present position of the pedestrian is calculated with:

$$E_{k+1} = E_k + S_k \sin(\varphi_k) \quad (4)$$

$$N_{k+1} = N_k + S_k \cos(\varphi_k) \quad (5)$$

$$H_{k+1} = H_k + \Delta H_k \quad (6)$$

where
the subscript *k* denotes the value at the step *k*.
E denotes the east position coordinate.
N denotes the north position coordinate.
H denotes the height coordinate.
φ is the heading with respect to the magnetic north.
ΔH is the height difference.
S is the step length.

The main program process is shown in Fig. 11. The initialization program includes the RCC clock configuration, I2C analog port initialization, the communication setting of USART and SPI, timer setting and the sensor configurations of MPU6050, HMC5883 and MS5607. The data is acquired and processed every 10 ms.

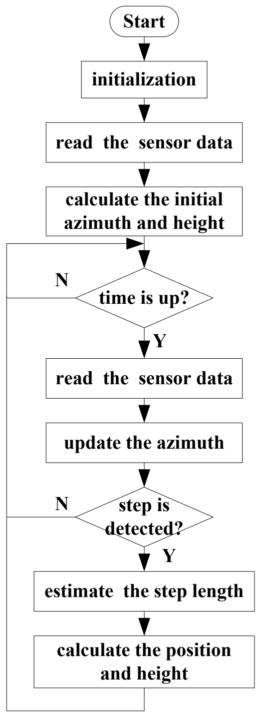

Fig. 11 The main program process

5. Experiments and Results

To evaluate the performance of the proposed hardware and algorithm, a series of field walking test experiments were conducted. The tests were designed to validate the performance without any support from GPS receiver. All experiments had been carried out in SYUCT(Shenyang university of chemical technology). The tests in the outdoor environment and indoor office building were performed respectively. The measurement system was mounted on the abdomen of the tester. The sensor data was captured at the sampling rate of 100 Hz. The data and position results were recorded using a notebook computer via the USB cable.

5.1 Outdoor Location Test

The first experiment was carried out in the chemical pyramid square of SYUCT. It is a circular area with a diameter of 60 m. The overall length of the tested route was approximately 188 m by 248 steps. The accuracy of the step detection algorithm is 100%. Fig. 12 shows the estimated trajectory of the outdoor test. In Fig.12, the blue curve is the real route of the tested area, and the black curve is the estimated route. A is the start point, and D is the end point. It is noted that the estimated curve is fit well from the start point A to point B. However, there is a slight angular error starting from point B. The error becomes greater and greater. The orientation error comes from the slight shaking of the sensor module and the magnetic disturbance from the metal building on the square. The maximum error between the final position estimation and the real route is about 7-m in the case, which accounts for a percentage of the total walking distance below 4%. It is validated that the positioning results strongly depend on the quality of the heading estimations.

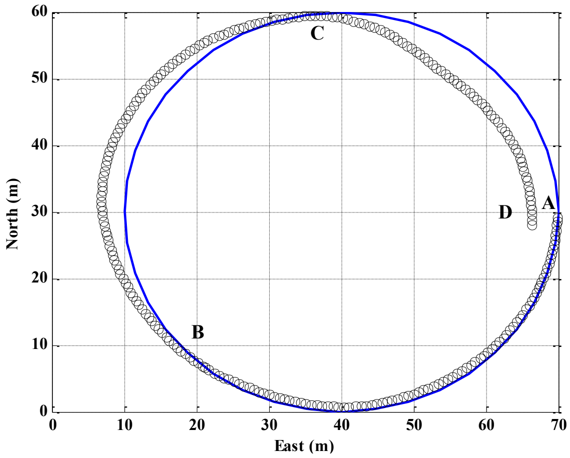

Fig. 12 The test result of the outdoor route

5.2 Indoor Location Test

The indoor location experiments were performed at the 3rd floor hallway of the 8th experiment building in SYUCT. The pedestrian trajectory of 174-m was examined three times. The path is straight with four 90-degree turns at the corners. The test result is shown in Fig. 13. In figure 13, the red line is the real path. The number of the detected step was 260, which was identical with the walking number of the pedestrian.

The maximal walking distance deviation is less than 5-m compared with the real route, which accounts for a percentage of the total walking distance below 3%. The reproducibility of the tracking error for a short operation time is favorable. The experimental results demonstrate that the total accuracy of the proposed PDR system is satisfactory.

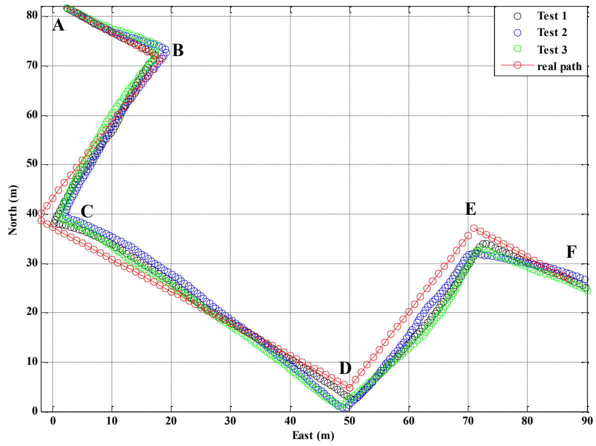

Fig. 13 The test result of the indoor route

6. Conclusions

The hardware and corresponding algorithms for the pedestrian navigation system are proposed. The hardware platform, without any fixed infrastructure, integrates GPS receiver and the low-cost, low-power and small-size MEMS inertial sensors which bridge the gaps of the GPS signal outages. The height is obtained from the barometer. The algorithms based on the accelerometer for step detection and step length estimation are presented. A complementary filter is proposed to fuse the digital magnetic compass, gyroscope and accelerometer for eliminating the heading error. Several walking tests were conducted to evaluate the system performance in outdoors and indoors with no GPS available. In the tests with the earth's magnetic field disturbances, the positioning error is less than 4% of the total traveled distance. The accuracy and reliability of the navigation system is satisfactory in measuring displacement of a pedestrian.

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