Research on Indoor Firefighter Positioning Based on Inertial Navigation

48

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Abstract

Because the situation around a fire is complex, such as heavy smoke, loss of electricity, and building collapse, many positioning systems are not able to work properly. Once the firefighters lose their sense of direction, this not only brings great psychological pressure to them but also causes hidden danger. Given that indoor positioning for firefighters is tough and existing locating systems are dependent on external references, inertial navigation is introduced to locate firefighter positioning. Based on analyzing the applicability of the inertial sensors in the fire ground, inertial measurement was designed. The algorithms of position estimation, step detection, and others are applied to complete this inertial system. Planar and three-dimensional scenarios were set to test the effectiveness of this system according to the situation in the fire ground and the gait of firefighters. It is found that the system has good accuracy in different scenarios and can provide planar positioning accurately.

Nomenclature

ΔT	Time difference
D	Actual distance
e_a	Total absolute error of three-dimensional scenario
E_a	Average absolute error
E_r	Average relative error
$e_{x,y}$	Absolute error in x–y plane
e_z	Absolute error of the z-axis
g	Gravity component
q	Quaternion
T_s	Time when velocity and acceleration are both zero (0)
Z_r	Average absolute error of the z-axis

Greek symbols

ω	Vector
x_i	Distance from start point (0, 0) to point (x_e, y_e)

48.1 Introduction

In recent years, increasingly complex structures have brought great challenges to fire reconnaissance and rescue work. In the 2008 Xinjiang "1.2 fire," the complexity of the building structure caused the entrapment and sacrifice of three firefighters in the course of searching and rescuing. In the "2.9 fire" in the CCTV building in Beijing, a commander was sacrificed in interior rescue; in the "2.1 fire" in Suzhou industrial park, a firefighter was not able to find the return route and was trapped and died while in search of victims; in the "1.1 fire" in Xiaoshan District, Hangzhou, three firefighters could not find the evacuation route and were sacrificed. In the same year, two firefighters who were

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trapped in collapsed debris died in the Beijing "1.2 fire." If real-time positioning of the firefighters had been available, rescue could have been launched according to their locations to minimize casualties.

48.2 Related Work

At present, research on a firefighter positioning and navigation system is still in its infancy worldwide. There are only a few relatively mature algorithms and positioning systems. Firefighter positioning requires the continuous availability of high precision and high reliability inside and outside the room. Little research has been done on a firefighter positioning and navigation system in China. Relevant research on this topic in other countries stays in the laboratory stage without providing mature products. Technically, a firefighter positioning and navigation system can be classified as a positioning system based on signals and a positioning system based on inertial navigation.

48.2.1 The Positioning System Based on Signals

At present, the signal medias used in positioning systems mainly include GPS, ultrasound, optical, infrared, RFID (radio frequency identification), WLAN (wireless local area network), Bluetooth, UWB (ultra-wideband, UWB), and the cellular communication network [1].

In 2006, Hofmann from Germany conducted a comparative experiment in a fire ground for IEEE802.11a, IEEE 802.11b, IEEE 802.11n, Bluetooth, and the IEEE 802.15.4 [2].

After 9/11, the University of California at Berkeley undertook the project of improving the software and hardware platform of firefighting and rescuing and developed a rescue equipment information system called FIRE [3]. It includes two parts: SmokeNet and FireEye. When firefighters go into a building with SmokeNet, SmokeNet can obtain information about their real-time locations and monitor their heart rates and the oxygen concentration of the fire ground. Although the system can provide the location of a firefighter, multiple reference nodes need to be deployed within the building in advance.

In 2007, Ciurana et al. [4] from the Polytechnic University of Catalonia, Spain conducted an indoor positioning system of range tracking by existing the wireless local area network (WLAN) infrastructure with the support of the European LIAISON program. The WLAN network has the characteristics of high speed and convenient deployment. After testing, the system of positioning precision can reach 0.9 m (66 % confidence interval).

In 2007, Thales from Air France developed the IPS (indoor positioning system) [5], and gained success in the test in Hampshire, UK. The system uses a UWB signal to enter the terminal worn by firefighters for relative positioning. Through the WiFi network, information is transmitted to a fire truck in the open air.

In 2007, Markus Klann et al. from Germany Fraunhofer Association put forward the concept of LifeNet [6]. LifeNet adapts an ad hoc sensor network to help firefighters navigate indoors by means of relative positioning.

48.2.2 Positioning System Based on Inertial Navigation

In 2002, the Swiss Institute of Technology Alliance Measurement Laboratory developed the PNM (Pedestrian Navigation Module) [7]. This system, which mainly performs DR (dead reckoning) without getting a GPS signal, is mainly used for blind navigation and a firefighter's emergency use.

In 2004, Jari Saarinen et al. from Finnish Helsinki University of Technology proposed the PeNa Navigation system (Personal Navigation system) in the European project PeLoTe [8] by using Kalman filtering fusion gyroscope and magnetometer data to estimate direction and measure step length with ultrasonic.

In 2005, InterSense in Germany proposed navigation shoes [9] (Navigationsschuh, referred to as "NavShoe"). Such technology as based on Navshoe applies a high-precision accelerometer and gyroscope fixed on the shoes of testers. Error both indoors and outdoors can be less than 1 %. Now, the error of navigation system positioning may be from 2% to 5 %.

In 2008, Oliver Woodman [10] from the University of Cambridge put forward a kind of navigation calculation method based on map matching, which uses a detailed building floor plan to correct the navigation position error of the prediction method combined with a particle filter algorithm to trace firefighters.

To sum up, among the existing indoor positioning technology, only a few methods do not rely on an external reference or technical datum. Inertial navigation technology is a completely independent way of positioning, which uses inertial measurement unit test data fixed on the user's foot to realize three-dimensional positioning in the scenario. Inertial positioning technology relies only on its own sensor and can do real-time positioning, so it has the characteristics of independence and does not rely on the external environment [11]. Therefore, this article focuses on the firefighters positioning system based on inertial navigation technology. An RFID tag is introduced as a reference point to correct the navigation and cumulative error produced in the calculation.

Therefore, the indoor positioning system can be used for firefighters, and is also suitable for underground work, tunnels, and other complex field operations.

48.3 Design and Implementation of Firefighter Positioning System Based on Inertial Navigation

The firefighter positioning system based on inertial navigation is mainly composed of an inertial measurement unit and a navigation prediction algorithm.

48.3.1 Design of Inertial Measurement Unit

An inertial measurement unit is the core of the positioning system hardware, and the whole system relies on the inertial measurement unit to obtain information about the firefighters' movements. Typically, the inertial measurement unit is composed of a variety of sensors. But as the environment of firefighting and rescue work is usually complex, with such problems as high temperature and smoke, some of the sensors cannot be applied to the firefighter positioning system. As a carrier to determine direction, the electronic compass, which is reliant on an external magnetic field and is susceptible to magnetic interference, cannot be used, especially in places where there are massive magnetic materials. In addition, although the barometric altimeter is a commonly used type of sensor, because firefighters often enter buildings through the smoke prevention stairwell where the positive pressure air supply system will be operating to prevent smoke from entering and the fire environment high temperature will also change air pressure [12], the barometric altimeter error is very large.

Considering the foregoing analysis, the firefighter selects only the three-axis accelerometer and gyroscope as the inertial measurement unit. Its design principle is shown in Fig. 48.1.

According to the design idea of Fig. 48.1, to facilitate and simplify the development of the system, the three-axis
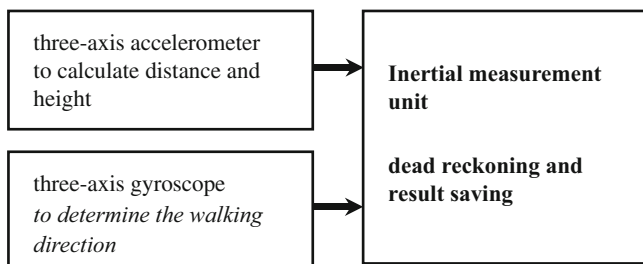

Fig. 48.1 Principal diagram of inertial measurement unit (IMU)

gyroscope and three-axis accelerometer of ADI Company are selected as the measurement unit to complete the inertial measurement; the performance parameters are shown in Table 48.1.

48.3.2 Firefighter Positioning System Algorithm Based on Inertial Navigation

The firefighter positioning system algorithm based on inertia is mainly divided into three modules, namely, the position estimation module, the stride length detection module, and the zero velocity update procedure (ZUPT).

48.3.2.1 Location Estimation

Because walkers will change gait constantly, the angle measured by inertial measurement unit is usually greater than 90°, so quaternions are chosen in the estimating Eq. 48.13 [13].

Quaternion q is a vector that represents the pacers gesture by the four parameters a, b, c, and d, which change with the angular rate, namely:

$$\dot{q} = \frac{q \bullet p}{2} \tag{48.1}$$

and $p = [0, \omega_b], \omega_b = [\omega_x, \omega_y, \omega_z]$

When a pacer's posture is calculated, the pacer's acceleration a_b can be obtained by using acceleration a_n in the inertial measurement unit system:

$$a_b = \frac{a_n}{q.q^*} \tag{48.2}$$

where q^* is the conjugate complex of quaternions q.

To minimize the error in the algorithm, the system also uses the discrete optimization algorithm. Speed v_n can be obtained by the integral of acceleration of gravity component g_t:

$$v_n = \int (a_n + g_l)\mathrm{d}t \tag{48.3}$$

Finally, the position can be obtained by the integral of speed:

$$p_n = \int v_n \mathrm{dt} \tag{48.4}$$

48.3.2.2 Zero Velocity Updated Technology

In the process of walking, there is a brief moment when the soles of your feet touch the ground and then leave the earth. In this brief moment, walking velocity can be thought to be

Table 48.1 Performance parameters of the inertial measurement unit (IMU)

Performance of sensor	Gyroscope	Accelerometer
Dimensions	Three axes	Three axes
Range	$\pm 1000°/s$	± 18 g
Linearity	0.1 % of FS	0.1 % of FS
Running deviation	0.003°/s	0.2 mg
Shaft to the shaft alignment error	0.1°	0.2°
Cross-axis error	1°	1°
Linear acceleration effect	0.05°/s/g	–

zero (0), and acceleration is zero as well. If at this moment the three axial velocities are not zero, the speed is produced by the cumulative error. To reduce the cumulative error, the algorithm will make the speed zero to avoid error accumulation in the next step. This is the zero velocity updated technology used in a positioning system.

48.3.2.3 Pace Detection Module

To ensure the normal operation of a zero velocity updated algorithm, it is not necessary for the positioning system to know exactly the start time and end time of ΔT. Only T_s is needed when velocity and acceleration are both 0 during ΔT. In practice, because of accelerometer drift, actual acceleration is not 0, so it is difficult to identify the T_s. Through experiment, T_s can be determined by observing three axial velocities (ω_x, ω_y, ω_z) of the angular velocity vector ω. Because in this period the absolute value of axial angular velocity is minimum, and angular velocity vector ω is determined by the three-axis gyroscope inertial measurement unit, so the time T_s can be easily determined and the experience can be applied to the following algorithm.

In the algorithm, the system divided the gyroscope signal ω_b into 100 sampling points, with each sampling point involving a data section of 0.5 s. The number of sampling points can be changed, mainly because the sampling point of time should be as short as possible, and the duration of the time should correspond to the time of required fastest pace, to ensure that there is a ΔT corresponding to each sampling point. At each sampling point, the system will calculate scalar array ω_s of $n = 100$; each element of ω_s is the amplitude of a scalar ω_b, namely:

$$\omega_{s,i} = \sqrt{\omega_{x,i}^2 + \omega_{y,i}^2 + \omega_{z,i}^2} \qquad (48.5)$$

In addition, the algorithm ω_s will also determine ω_T less than the threshold Ω. The eligible elements will make up the new array, with results as follows:

$$\omega_{T,i} = \begin{cases} \omega_{s,i}, \omega_{s,i} < \Omega \\ K, \omega_{s,i} \geq \Omega \end{cases} \qquad (48.6)$$

If all the elements in $\omega_{T,i}$ are K, it can be determined that ΔT does not exist in each sampling point; If one or more $\omega_{T,i} \neq K$, it is necessary to determine the minimum K value and the corresponding time T_s. Through the test, it is found that when the foot is still staying in the air, occasionally the algorithm mistakenly will deem the foot to have fallen onto the earth and the total rotation speed is lower than the threshold Ω. To eliminate this kind of miscalculation, the system will determine the position of feet by observing the accelerometer data.

By applying to the preceding algorithm, the sensor is also debugged. The following section is the test on the whole positioning system.

48.4 Test

Under different scenarios, the inertial positioning system is tested with the combination of possible gaits of firefighters in a rescue mission. The obtained data are analyzed and processed. By calculating the position precision, the applicability in firefighter positioning is determined.

48.4.1 Planar Scenario Testing

Because of the complex and changeable situation in the firefighting and rescue environment, firefighters will change their gaits according to the actual situation, such as running, walking, walking back, side walking, crawling, etc. They will also turn in direction or jump. To ensure that the positioning system can effectively function in various situations, this test will examine the graphic scenarios previously mentioned, respectively, to determine whether the positioning system can effectively identify and calculate the gaits. Test scenarios are shown in Fig. 48.2. The test is divided into two main parts: the first part is running, walking, walking while turning, and walking while jumping (including jumping upward and leaping forward ten times for each). A closed-loop path scenario test will be taken, that is, from the starting
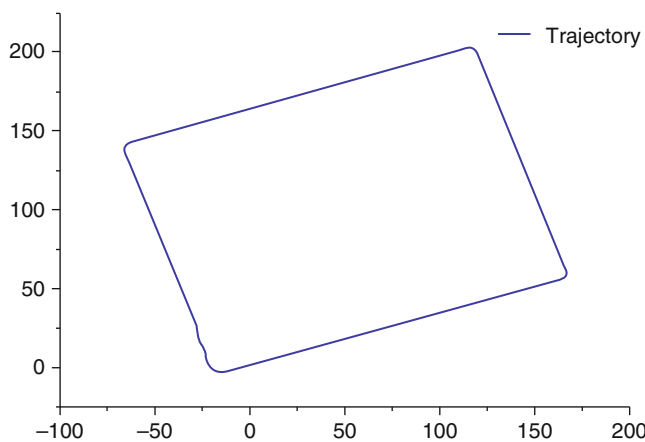
Fig. 48.2 Testing scenario

Fig. 48.3 Trajectory of first walking test

point and finally returning to the beginning. The test will be conducted alongside the path marked in blue in Fig. 48.3; the second part is walking backward, side walking, and crawling. The path for testing scenarios is straight with a distance of 100 m.

48.4.1.1 Planar Closed-Loop Scenario Testing

Under the closed-loop path scenario of running, walking, walking while turning, and walking while jumping scenario, the tester will perform in accordance with the path shown in Fig. 48.2. The testing distance, D, is 700 m. It starts from any starting point and to the ending along the path. Each gait will be tested three times. Figure 48.3 shows the trajectory of the first walking test.

Because starting point and end point are at the same position in the test, and the coordinates of the starting point are (0, 0), so the absolute error E_a of the positioning system in the plane can be determined by the terminal coordinates:

$$E_a = \sqrt{x_e^2 + y_e^2} \tag{48.7}$$

where x_e is the position error on the x-axis; y_e is position error on the y-axis.

The average absolute error E_a calculation equation is as follows:

$$E_a = \frac{1}{n} \sum_{i=1}^{n} e_{a,i} \tag{48.8}$$

The average relative error E_r is calculated by the following equation:

$$E_r = 100 \frac{E_a}{D} \tag{48.9}$$

Figure 48.4 is a closed-loop path after testing the gait. The end position (x_e, y_e) in the x–y axis is the position error in relationship with the starting position (0, 0).

Table 48.2 shows the average error analysis of the test results. The errors in the tests are mainly influenced by two factors: one is in the linear displacement distance estimation, and the other is the heading error.

48.4.1.2 Planar Straight Scenario Testing

In the straight-line scenario test of walking backward, side walking, and crawling, the test distance D is 100 m. Each gait is tested three times. For linear test results, because in actual tests the coordinates of the starting point are (0, 0), the distance can be determined by the destination coordinates (x_e, y_e):

$$x_i = \sqrt{x_e^2 + y_e^2} \tag{48.10}$$

The average absolute error calculation X_a method is as follows:

$$X_a = \frac{1}{n} \sum_{i=1}^{n} |x_i - D| \tag{48.11}$$

Using the following equation to calculate the average relative error X_r (average error X_r of the proportion of walking distance):

$$X_r = 100 \frac{X_a}{D} \tag{48.12}$$

Table 48.3 shows the average error of results of walking backward, side walking, and crawling. This experiment mainly evaluates the inertial measurement unit by measuring the linear movement in walking backward, side walking, crawl, and accuracy of the system. Average relative error of the system in walking backward, crawling, and walking sideways are 1.02 %, 0.26 %, and 0.99 %, respectively. The

Fig. 48.4 Position errors of
closed-loop 2-D path
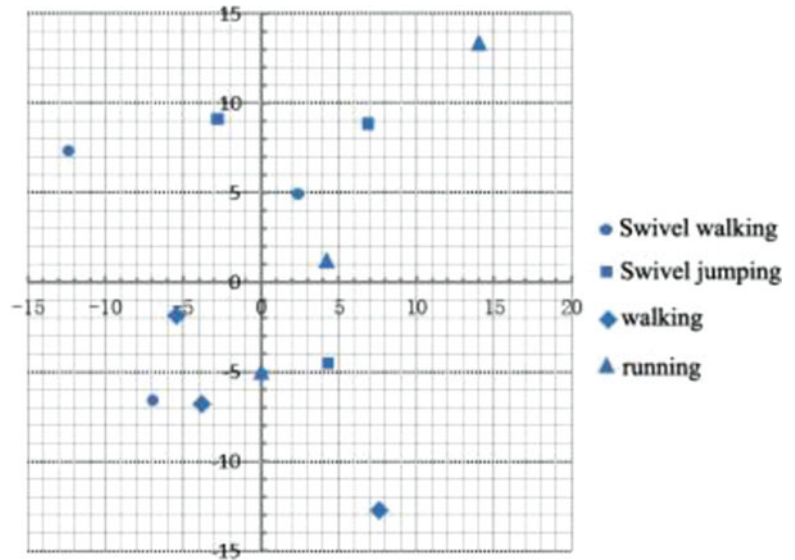
Table 48.2 Test results of the closed-loop 2-D path

Gait	Number	Actual distance D (m)	Reckoning error e_a (m)	Average absolute error E_a (m)	Average relative error E_r (%)
Walking	1	700	1.66	1.57	0.22
	2	700	1.65		
	3	700	1.40		
Running	1	700	1.92	1.86	0.27
	2	700	1.75		
	3	700	1.90		
Swivel walking	1	746	2.84	3.01	0.43
	2	753	3.19		
	3	741	3.01		
Swivel jumping	1	700	2.31	1.99	0.28
	2	700	1.69		
	3	700	1.97		

Table 48.3 Test results of the straight-line scene

Gait	Number	Actual distance D (m)	Reckoning error x_i (m)	Average absolute error E_a (m)	Average relative error E_r (%)
Walking backward	1	100	101.37	1.02	1.02
	2	100	101.26		
	3	100	99.56		
Side walking	1	100	100.39	0.26	0.26
	2	100	99.80		
	3	100	100.18		
Crawling	1	100	100.98	0.99	0.99
	2	100	99.21		
	3	100	101.20		

errors are small, which can well meet the needs of firefighters.

In the test of normal walking, running, walking while jumping, and side walking, the system position error is no more than 0.5 % of the walking distance. In the tests of crawling and walking backward, however, the accuracy of the system relatively declines and the error is about 1 %.

48.4.2 Three-Dimensional Scenario Test and Analysis

In the positioning system, the three directions of the velocity vector apply to the technology of zero velocity updating. Thus, it can calculate not only in the x–y plane position, but also be measured for the z-axis position. In this way, three-dimensional scenario positioning can be realized.

The test will be conducted in three-dimensional space. On both sides of the test scenarios there is a six-layer square construction of stairwell for smoke prevention. It is mainly used to test the accuracy of the inertial measurement unit position in the three-dimensional scenario. The tests will be on the positioning system through normal walking and running. The test will be done three times in each case. The tester goes from a layer along the east side of smoke stairs up to the top. Then the tester goes through a corridor to the west side of the smoke prevention stairwell, and from there under the smoke prevention stairwell to a layer and back to the starting point. In this way, a closed-loop path test is done.

The test absolute error of the results on the x–y plane for the three-dimensional scenario can be calculated by Eq. 48.7. The average absolute error on the z-axis can be calculated with the following equation:

$$e_z = \frac{1}{n}\sum_{i=1}^{n}|z_{e,i}| \qquad (48.13)$$

The average relative error of the z-axis can be calculated by the following equation:

$$z_r = 100\frac{e_z}{H} \qquad (48.14)$$

H is the highest point that the test instrument reaches in the three-dimensional scenario.

The total absolute error e_a of the three-dimensional scenario can be calculated by the following equation:

$$e_a = \sqrt{e_{x,y}{}^2 + e_z{}^2} \qquad (48.15)$$

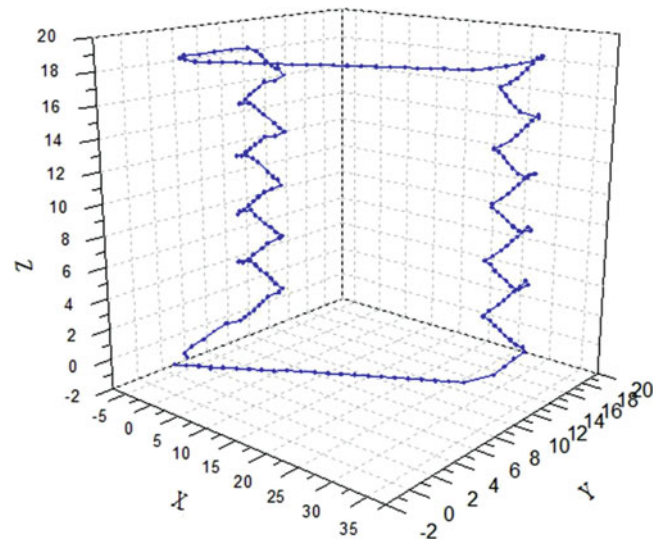The average relative error can be calculated by the equation:

Fig. 48.5 First walking trajectory in 3-D closed-loop scene

$$E_r = \frac{1}{n}\sum_{i=1}^{n}\frac{e_{a,i}}{D_i} \qquad (48.16)$$

In the whole test, testers will do a closed-loop path test including going up and down the stairs along the building. Figure 48.5 shows one test in 3-D trajectory. Figure 48.6 shows the error of the x–y plane. Table 48.4 shows the test results.

In this test, the average relative errors of the positioning system under normal walking and running are 0.77 % and 0.82 %, respectively.

48.4.3 Rolling Terrain Closed-Loop Scenario Test and Analysis

The complexity of the disaster scenario environment may cause indoor firefighters to encounter a collapsed ceiling. The test scenario at this time will be turned from a horizontal ground into rolling terrain. Therefore, the positioning system must be able to accurately predict the firefighter walking tracks on rugged topography.

This method is mainly used to test performance of the state of a positioning system when climbing through rubble. The test site would be at rubble composed of large pieces of broken concrete and soft soil as high as 2.5 m (Fig. 48.7). The first test trajectory is shown in Fig. 48.8. During the test, the tester will go over the rubble along a certain path back to the starting point three times in all. The total absolute error can be determined by Eq. 48.15. The average relative error can be calculated by Eq. 48.16.

Fig. 48.6 Position errors of *x–y* plane in 3-D scene
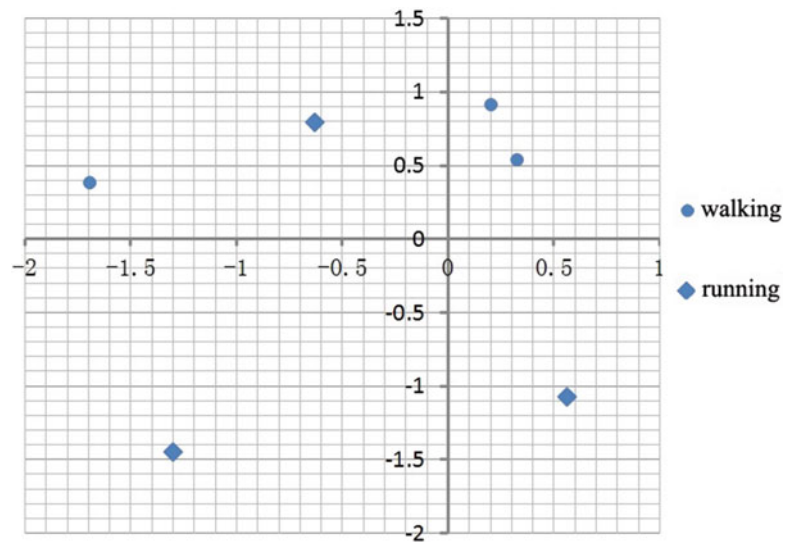
Table 48.4 Test results of the 3-D scene

| Gait	Number	Actual distance D (m)	Climbing height H (m)	Average absolute error E_a (m)	Average relative error E_r (%)
Walking	1	211.40	18.7	1.79	0.77
	2	212.59	18.7	0.97	
	3	215.49	18.7	2.16	
Running	1	216.97	18.7	1.60	0.82
	2	218.72	18.7	1.22	
	3	215.62	18.7	2.50	

Fig. 48.7 Scene of rugged terrain

Under these conditions, because the tester's feet often slip, the inertial measurement unit test is relatively difficult. The specific test results are shown in Table 48.5; the average relative error is 0.91 %.

48.4.4 Long-Time Walking Test and Analysis

When the firefighters are putting out the fire or launching the rescue campaign in the buildings, they usually need to spend
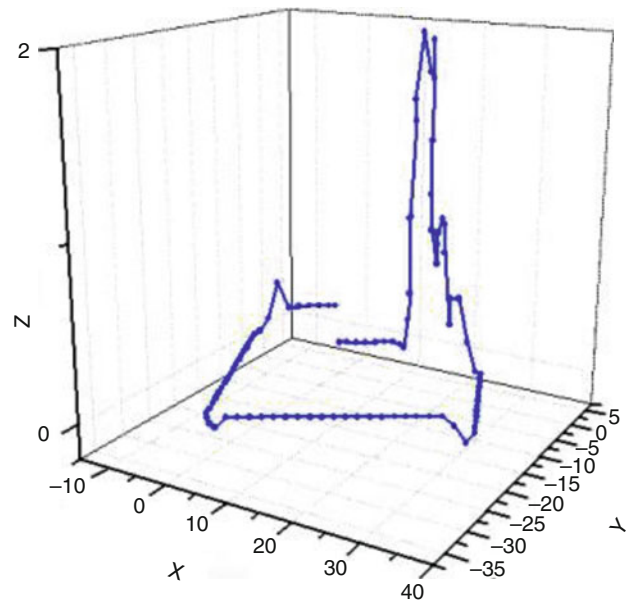
Fig. 48.8 First trajectory in the rugged terrain scene

some time in the building. If the task is undertaken in strenuous and complicated situations, it takes as long as 20–40 min or even much longer. Therefore, a long-time walking test is conducted to meet the practical requirement of firefighters.

Table 48.5 Test results of the rugged terrain scene

Number	Actual distance D (m)	x absolute error (m)	y absolute error (m)	z absolute error (m)	Total absolute error E_a (m)	Average relative error E_r (%)
1	131	0.18	0.94	−0.19	0.98	0.91
2	128	1.54	0.565	−0.35	1.68	
3	128	−0.79	0.20	0.23	0.85	

Fig. 48.9 Path of long-duration tests under walking

Fig. 48.10 Path of long-duration tests under mixed gaits

The positioning accuracy test will be conducted in both normal walking gaits and mixed walking gaits (including walking, running, jumping, walking back, walking horizontally, leaping, and turning), with each case twice. The mixed walking path is shown as a white line in Fig. 48.9; a normal walking path is shown as the white line in Figs. 48.10 and 48.11; Fig. 48.12 shows the trajectory of the tester; and Table 48.6 shows the test results. In data analysis, Eq. 48.7 can be used to calculate absolute error and the average absolute error can be calculated by Eq. 48.8. The average relative error can be calculated by the following equation:

$$E_r = \frac{1}{n} \sum_{i=1}^{n} \frac{e_{a,i}}{D_i} \qquad (48.17)$$

Results show that the testing error is large because of the accumulated error under the condition of long-time walking. However, a rough estimate of its location can be determined by the firefighter indoor positioning system. In the long-time test, for reasons such as gyroscope drift, the absolute error of the system increases although the relative error is less than 1 %.

48.5   RFID Auxiliary Corrections

The short-range interaction of RFID greatly simplifies the identification process of equipment interconnection. Compared with other short-range wireless communication technology, RFID is safer with shorter reacting time; thus it becomes a new hotspot of the mobile communications industry, which has broad applications in the future. This system proposes that the RFID technology can assist inertial navigation and positioning technology and rapidly correct accumulative errors caused by inertial navigation. Also, the low cost of RFID is advantageous for its popularization. Figure 48.13 shows the results of an RFID network test on the fourth floor of the laboratory with a total of 12 rooms. Each room is installed with a RFID reader, and numbers inside the orange circle in Fig. 48.13 represent a different RFID reader. Numbers in the green circle are walking testers carrying RFID tags in the corridor. Finally, testers can record the position in the system, which indicates that RFID network positioning succeeds.

Fig. 48.11 First trajectory of long-duration tests under walking
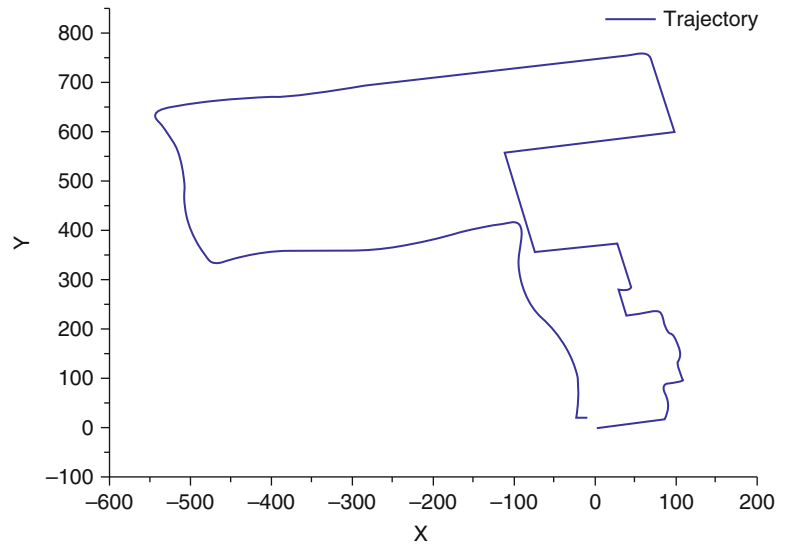
**Fig. 48.12** First trajectory of long-duration tests under mixed gaits
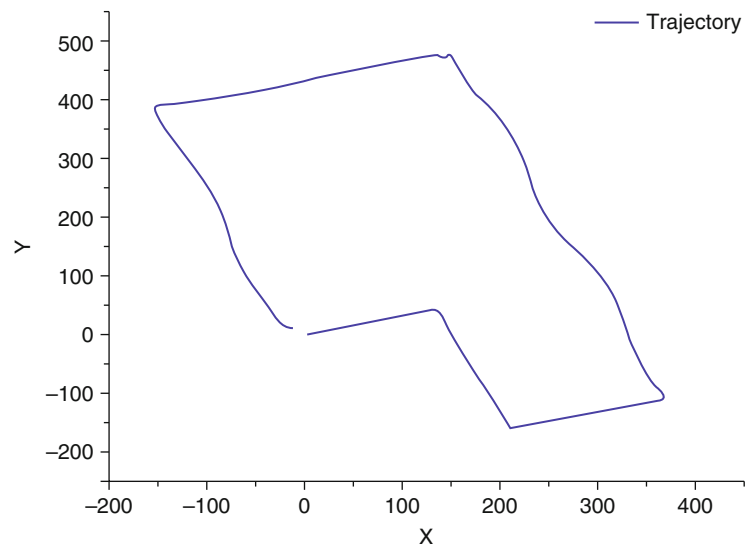
Table 48.6 Test results of the long-duration walking

Gait	Time T (s)	Actual distance D (m)	Absolute error (m)	Average absolute error (m)	Average relative error (%)
Walking	1910	3014	20.11	17.59	0.58
	1950	3045	15.06		
Mixing	1345	1876	19.58	16.11	0.86
	1320	1883	12.63		

48.6 Conclusions

The biggest advantage of positioning based on the technology of inertial navigation lies within its completely independent way of positioning, which can meet the demands of firefighter positioning in the scenarios of complex disasters. In combination with a variety of tests of gait under different situations, the positioning system based on inertial technology has a higher positioning accuracy, which can roughly estimate which floor the firefighter is on as well as the room location. In future work, we will look for a method to

Fig. 48.13 Signal test pattern
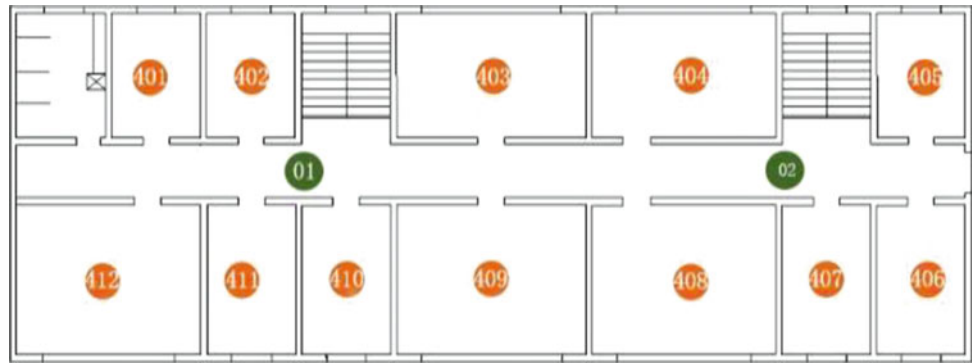
minimize error with the increase of distance to improve the accuracy of the positioning system.

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