Knee and Waist Attached Gyroscopes for Personal Navigation: Comparison of Knee, Waist and Foot Attached Inertial Sensors

Zexi Liu
Department of Electrical Engineering
Drexel University
Philadelphia, USA
Dunkirk_16@hotmail.com

Chang-Hee Won
Department of Electrical & Computer Engineering
Temple University
Philadelphia, USA
cwon@temple.edu

***Abstract*—We perform personal navigation using inertial sensors at knee, waist and foot positions. We found out that the knee attached gyroscope gives the best distance traveled information. The proposed system at the knee takes advantage of the fact that the angular displacements repeats at each period (each step of the walking person). Using this period, the system will keep the angular displacement errors bounded. Also, the waist attached gyroscope gives the best heading information. Consequently, we propose a personal navigation system that consists of gyroscopes at the knee and waist. The system performance was evaluated with a number of indoor experiments and the experimental results showed that this configuration provide better position information compared to other configurations. The system performs well even when the person is climbing stairs.**

Keywords- Personal navigation; Inertial sensors; Gyroscopes; Indoor Navigation.

I. INTRODUCTION

Knowing the location of a person has many interesting applications such as an emergency responder or a miner tracking. For outdoor operations, several techniques such as Global Positioning System (GPS) and cellular-based methods are extensively used. For indoor operations, there is radio-frequency identification (RFID) based positioning technique. This RFID technology requires initial hardware installation in the building with the known floor plans. However, there is a need to track a person inside the building without any a priori knowledge of the infrastructure.

Several studies have been carried out to track and position a walking person [1-9]. The simplest implementation is attaching a single accelerometer on the waist of a walking person [1]. This accelerometer will measure the vertical hip acceleration because there is a relationship between vertical hip acceleration and the stride length of a walking person. However, this method cannot provide the heading information. Moreover, the relationship is nonlinear and depends on the individual. Another study improves this method by measuring both the forward and vertical acceleration. In addition, it gives out heading information by measuring the angular rate [2]. The waist attached inertial sensor, however, gives inaccurate results, as we will show by comparing with other methods.

Sensors have also been attached to other parts of human body. Several studies have proposed to attach sensors near the foot. This is a straight forward method since the step length can be calculated directly based on foot acceleration information [3-7]. We will compare this foot attached method with our knee attached method. This method is also less accurate than our knee based method. Moreover, both waist and foot attached method does not work when a person is running or climbing stairs.

There are also some other solutions developed in personal navigation. Parviainen *et al.* proposed a method to improve the accuracy and the availability of the altitude information by using a differential barometry [8]. An indoor processed measurement was presented by keeping the barometry in the hand while walking around the building and taking an elevator. Different floor levels can be identified from their experimental results. Frosio *et al.* developed automatic calibration method of MEMS accelerometers for tracking the motion of human beings [9]. Liu *et al.* performed a combination of three gyroscopes that measure the rotational velocity of the foot, shank and thigh, and a two-axis accelerometer to measure accelerations. This system detects the angle of inclination from measurements of two-directional accelerations projected by gravity acceleration [10]. However, these methods suffered from large vibrations and uncertainties brought by the foot movement.

In some studies, sensors are attached to two knees, two feet, waist, and head [11, 12]. With enough hardware, relatively accurate personal navigation is possible, however, we would like to determine the minimum number of sensors necessary for personal navigation. As stated in [13], "There is a clear need for a light-weight, low-power personal navigation system that provides accurate geo-location with low dependence on external reference sources, such as GPS."

Our objective is to use minimum number of sensors and obtain "good" positioning accuracy. We investigate different sensors and configurations. In this work, experiments were conducted using inertial sensors for a robust personal navigation. Because there are different motions on different parts of human body, the inertial sensors are attached to three different parts of human body: waist, knee and foot as shown in Figure 1. In each of these cases, data have been collected on a walking person, corresponding distance calculation and heading angle calculation have also been developed. A comparison in regards to the sensors selected, the motion features, the signal characteristics, calculation methods and experimental conditions among these three configurations have been carried out. Here, we propose to use two gyroscopes, one attached to waist and one attached near the knee. The sensors at the knee will measure the angular rate of leg swing and the sensor on the waist will measure the angular rate of turning. As a result, both distance and heading information can be obtained. Furthermore, our method does not suffer from cumulative errors because the acceleration data is not used. Our method is patent pending [14].

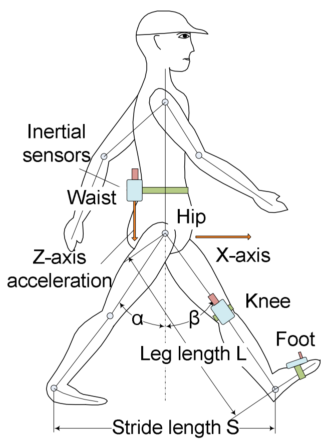

Figure 1 Different deployments of sensors

II. Knee Attached Gyroscope

We used a gyroscope data to obtain the distance traveled information. The details of this method and the experimental results are given in this section.

2.1 Distance Calculation Method

When a gyroscope was attached to the lower thigh (just above the knee) of a person's leg, the angular rate of leg movement can be measured using only one gyroscope. Angular displacements α and β can be determined by integrating the angular rate of leg movement. Using the law of cosines, the stride length *S* can be calculated as follows:

$$S = L\sqrt{2\cdot[1-\cos(\alpha+\beta)]} \tag{1}$$

where α and β are angular displacement; L is the leg length as shown in Figure 1. Unfortunately, as long as there is integration, the errors will be accumulated. To bound the error, a new method, called *Zero Angular Displacement Update* (ZADU), was introduced in this work. The key idea is to reset the displacement value back to zero at a certain period of time. This period is exactly one step of the walking person. The integral is carried out separately in each period (i.e., step) so the initial value of each integral is always zero. Thus, the next iteration does not include the errors from the last calculation.

Figure 2 demonstrates angular displacements of leg movements. The curve with asterisk is the results of angular displacements of leg movements using a direct integral while the other solid line shows the results of angular displacements of leg movements with the ZADU method. Apparently, the algorithm with ZADU does not degrade with time. Therefore, the algorithm with ZADU has been applied to estimate angular displacement of leg movement. Then the stride length is obtained using Eq. (1). By summing up all the stride lengths, the distance D that a person has walked can be determined. Let ***N*** be the total number of strides and ***n*** indicates each stride, the distance D can be written as

$$D = \sum_{n=1}^{N} stride(n) = \sum_{n=1}^{N} L\sqrt{2\cdot[1-\cos(\alpha+\beta)]} \tag{2}$$

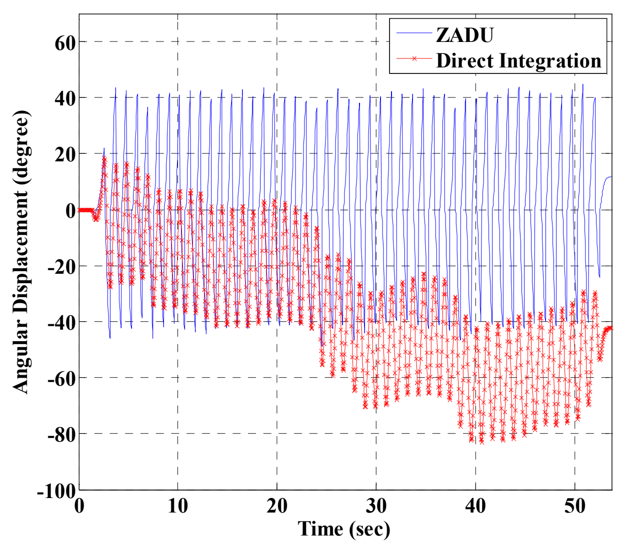

Figure 2 Angular displacement of leg movements

2.2 Experimental Results for Knee Attached Sensor

The distance traveled experiment is conducted for the knee attached gyroscope. See Figure 3 for the test route, which is the 7th floor of the Engineering Building, Temple University. The sampling rate was 19.7 samples/second. Twenty trials have been conducted to estimate the distance of a walking person using the knee attached gyroscope with ZADU. The results are given in Table 1. Condition A denotes that the real distance is 96.18 m with six perpendicular turnings; condition B represents a person walking at a constant speed; condition C stands for a person walking at a variable speeds; condition D signifies that the experimenter did not stop during the length of travel; and E refers to the experimenter stopping three times during the experiment. Also, STD indicates standard deviation. For example, trials 1 to 10 are for a person walking at a constant speed without stopping for the distance of 96.18 meters.

The test route length of 96.18 m was manually measured, and this is taken as the true distance. Trials 1~10 are under the conditions of constant walking speed without any stops during tests. The relative error of 0.11% was obtained. Trials 11~15 are under the conditions of constant walking speed with three stops during tests. The relative error of 0.46%. Trials 16~20 are under the conditions of variable walking speed without stops during tests. Relative error of 0.64%. Although it is not shown in the table, we tried the experiment with different sampling rate of 76.3 samples/second. This did not make much difference on the result. In fact, we note that walking at different speed nor with or without stops did not make much difference in the results. We conclude that a gyroscope with ZADU algorithm give accurate distance traveled information.

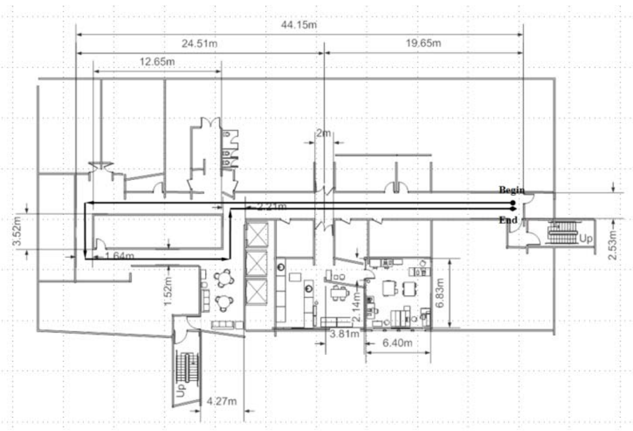

Figure 3 Test Route for the Experiments

Table 1 Trial results in distance calculation with a knee attached gyroscope (sampling rate 19.7 Hz)

Trial No	Cond.	True steps	Measurement Steps	Measurement Distance (m)	Statistical analysis Mean (m)	Statistical analysis STD (m)
01		124	125	94.14		
02		124	124	96.17		
03		125	127	96.99		
04		124	123	97.70		
05	A,B, D	124	125	95.66	96.29	0.9977
06		122	121	96.17		
07		125	127	96.45		
08		125	125	96.69		
09		126	127	97.25		
10		124	123	95.72		
11		125	138	97.69		
12		125	138	96.03		
13	A,B, E	123	136	96.67	96.62	0.6563
14		125	138	96.54		
15		125	136	96.15		
16		124	123	96.21		
17		121	121	95.26		
18	A,C, D	120	121	94.87	95.56	0.5431
19		120	119	95.48		
20		122	121	95.99		

Note: Cond. stands for conditions.

III. WAIST ATTACHED SENSORS

We compare our knee attached inertial sensor configuration to other configurations such as the waist attached accelerometer configuration.

3.1 Distance Calculation Method

The hip and by extension the upper body moves vertically when a person walks. The vertical acceleration is measured by attaching an accelerometer near the waist of a person. The frequency of leg movement while walking is about 2~3 Hz, so the sampling rate is selected as 20 Hz. Figure 4 shows a filtered acceleration signal from a walking person. The right upper part of Figure 4 denotes the vertical movement of hip while walking. From Figure 4 the beginning and the end of one stride can be clearly identified.

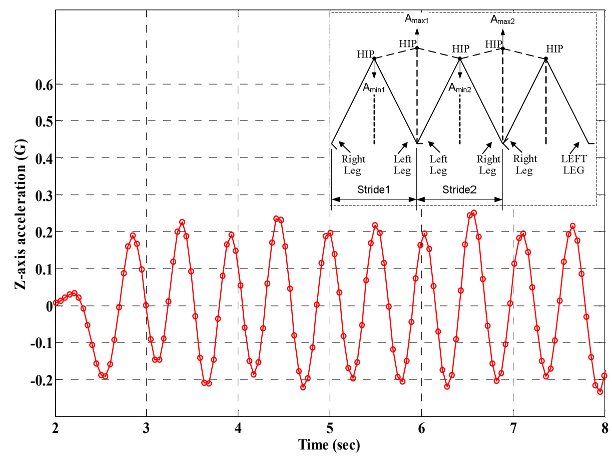

Figure 4 Vertical movement of hip while walking and acceleration signals

We established a relationship between the maximum and minimum amplitude difference, $A_{max} - A_{min}$ and the stride length S. Basically, if the stride length gets longer, the $A_{max} - A_{min}$ will be larger. In order to obtain the relationship, an empirical curve was employed. By counting the positive peaks (A_{max}) and negative peak (A_{min}) of the above waveform, how many steps that a person has walked and how many times the waveform crosses zero is calculated. Nine different stride lengths, 0.31, 0.38, 0.46, 0.53, 0.61, and 0.68 meters, were applied. This means that the person walked using these 9 different stride length and recorded the vertical acceleration (Z-axis) data. Grand total of 135 trials were carried out. By using polynomial fitting, the relationship between $A_{max} - A_{min}$ and the stride length S is derived from the empirical equation below:

$$\begin{aligned} S(n) \approx\ & 30.39\left(A_{max}(n)-A_{min}(n)\right)^3 - 29.88\left(A_{max}(n)-A_{min}(n)\right)^2 \\ & +12.96\left(A_{max}(n)-A_{min}(n)\right)+0.43 \end{aligned} \tag{3}$$

Figure 5 shows the experimental data and the fitted curve. Generally, all the stride lengths are summed up to obtain the distance that a person has traveled. Let N be the total number of strides and let n indicates each stride S, then the distance traveled is given by:

$$\text{Distance} = \sum_{n=1}^{N} S(n) = \sum_{n=1}^{N} f\left[A_{\max}(n) - A_{\min}(n)\right]. \quad (4)$$

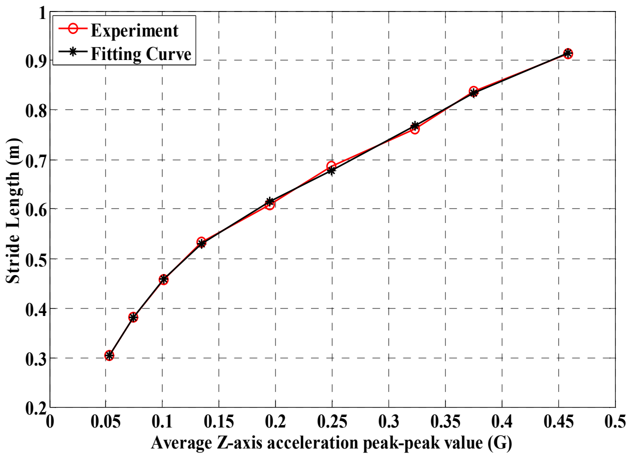

Figure **5** Experiment data Curve Fitting

3.2 Experimental Results for Waist Attached Sensor

The accelerometer was attached to the waist of a walking person. During the experiment, this person will walk along the test route given in Figure 3. We perform the test with different conditions such as constant speed, variable speed, with or without stops. The true distance of 96.18 meters was measured by an accurate measuring wheel. The data gathered from the inertial sensors are processed by Matlab. We have performed total of twenty-six trials.

Table 2 Test results of distance calculation with waist attached accelerometer

File name	Cond.	Test Results	
		Distance (m)	Error (m)
D_01	A, B,	88.28	7.90
D_02	D	97.97	1.79
D_03		96.83	0.65
D_04		99.12	2.94
D_05		120.83	24.65
D_06		122.53	26.35
D_07		115.08	18.90
D_08		113.89	17.71
D_09		115.56	19.38
D_10		110.99	14.81
D_11		107.87	11.69
D_12		113.67	17.49
D_13	A, C,	93.47	2.71
D_14	D, E	124.48	28.30
D_15		103.63	7.45
D_16		109.84	13.66
D_17		100.33	4.15
D_18		101.09	4.91
D_19	A,	88.85	7.33
D_20	B, E	81.12	15.06
D_21		94.39	1.79
D_22		105.81	9.63
D_23		106.19	10.01
D_24		107.24	11.06
D_25		106.79	10.61
D_26		111.65	15.47
Average		105.29	11.78

It is obvious from Table 2 that the method is not very reliable for precise navigation. The error is up to 28.30 meters. Even the average error is 11.78 meters. This error is significant compared to the total length of the route. The relative error varies greatly from 0.68% to 29.4%.

IV. FOOT ATTACHED SENSORS

In this section, we consider inertial sensors attached to the foot as in [3-7]. An accelerometer and a gyroscope is attached to the foot. Using the foot acceleration and angular rate, the distance travelled is estimated.

4.1 Distance Calculation Method

A foot attached accelerometer will measure the acceleration of the foot. So the speed and displacement is calculated from the acceleration. The key lies in that the zero-velocity should be updated while the foot is at a standstill. These updates should be correctly performed at every step otherwise the position drifts very quickly. This method is called the zero-velocity updates (ZUPTs). In this method, a foot standstill is detected when acceleration and gyro sensor readings both drop below experimentally specified thresholds. Similarly, a foot movement is detected. In Figure 6, the upper plot is the product of x-axis acceleration and y-axis angular rate. The lower plot is the x-axis acceleration. It is easier to determine the standstill period from the upper plot. We use x-axis acceleration and y-axis angular rate to determine the standstill period. Once the standstill period has been determined, velocity is calculated by integration. Furthermore, the velocity will be reset to zero whenever there is a standstill period. By using this method, the drift becomes bounded.

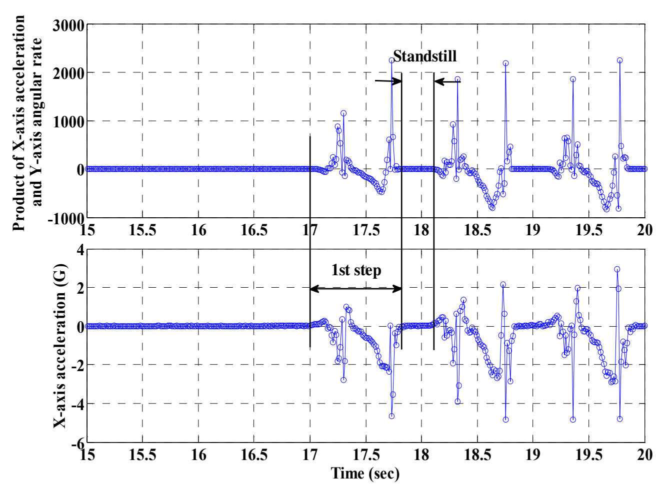

Figure 6 Movement and standstill period determination

The key of this method is resetting the velocity to zero after each step. Without resetting, there will be a large bias error in the distance calculation. Figure 7 shows the calculation results based on ZUPTs. In Figure 7 the top figure is the acceleration; the middle figure is the velocity, and the bottom figure is the distance. Only the acceleration is measured by sensors. The velocity is calculated based on acceleration and the distance is calculated based on the velocity. This integration introduces significant error.

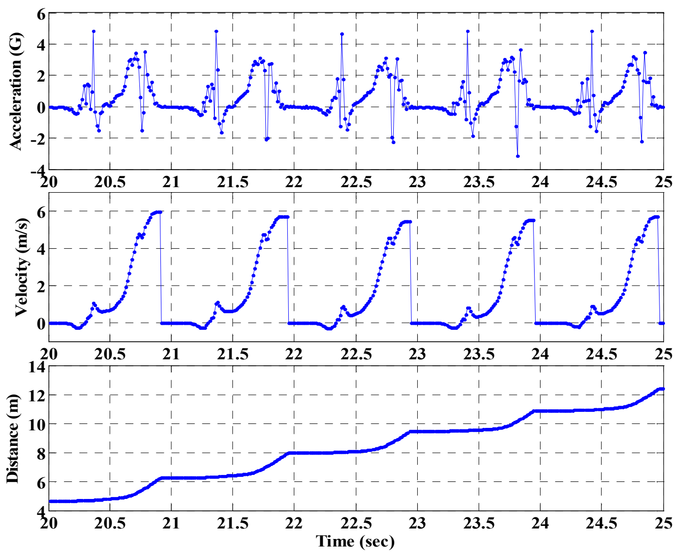

Figure 7 Distance calculation using ZUPTs

4.2 *Experimental Results for Foot Attached Sensor*

The same test routes as the other experiments were used in this experiment. The true value is 96.18 m in all experiments and the sampling rate was 76.3 Hz. Under four turns, the average distance is 93.12m with a standard deviation 3.54m; under a variable walking speed, the average distance is 88.75m with standard deviation 3.23m; with multi-stops, the average distance is 94.13m with standard deviation of 1.85m. It is noted that the knee attached gyroscope is better in distance calculation than the foot attached accelerometer. The knee attached gyroscope gave 96.19 m, whereas the foot attached accelerometer gives 92.07 m as the final result. Moreover, the standard deviation of the knee attached gyroscope is much smaller than the foot attached accelerometer, which means the latter have larger variance.

V. HEADING INFORMATION ESTIMATION

5.1 *Heading Angle Estimation*

Gyroscope attached at the knee or waist could provide precise heading information. So, we used the gyroscope attached to waist. Here we describe how the heading information is calculated from the angular rate provided by the gyroscope. The gyroscope provides the angular rate D (see Figure 8). We obtain the heading change angle by the following equation.

$$\theta(k+1) = \theta(k) + \frac{1}{2} \times [\omega(k) + \omega(k+1)] \times \frac{1}{f} \qquad (5)$$

where θ is the heading angle (degree); ω is the angular rate (degree/second); k is a serial number; f is the sampling rate.

5.2 *Experimental Results*

The relative heading of initial heading direction is calculated. Test results in heading calculations with the sensor at the waist are shown in Table 3. The heading error of the knee configuration almost reached 18 degree/turn, which is much bigger than that of the waist configuration (1.7 degree/turn).

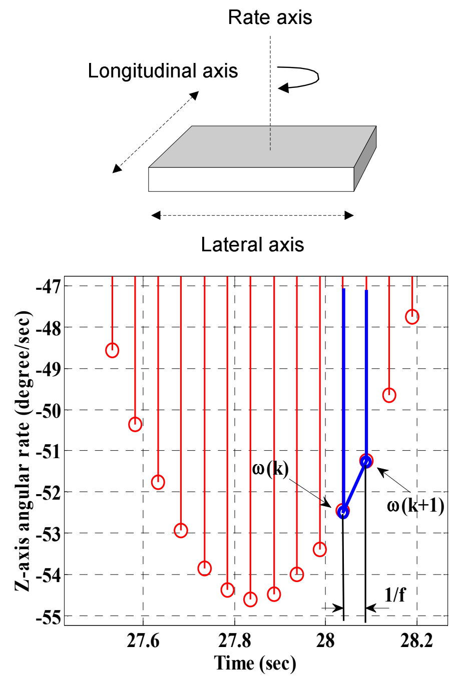

Figure 8 Gyroscope and Z-axis angular rates

Table 3 Trial results in heading calculation with the waist attached gyroscope

Trial No	Number of 90º turning	Calculated Heading Value	Error	Error/ turning
D01	4	366º	6º	1.5º
D02	4	353º	7º	1.8º
D03	4	368º	8º	2.0º
D04	4	351º	9º	2.3º
D05	4	355º	5º	1.3º
D06	4	355º	5º	1.3º
Ave.	4	358º	6.67º	1.7º

Note: Ave. stands for average. The true heading value is 360º.

It is noted that the inertial sensor-gyroscope may be affected by drift errors when it is attached to human body, so Eq.(5) produces cumulative errors in a multi-step walking motion analysis. The experimental results in Table 3 show that an average error of 1.7 degrees/turn, which is acceptable for calculating the heading angle. However, the error will accumulate, if the number of turns increases.

VI. COMPARISON OF THREE CONFIGURATIONS

The experimental results have demonstrated that the percent error of the knee configuration is 0.74%; the percent error of the waist configuration is 9.47%; and the error of the foot attached configuration is 4.27%, respectively. The results show that the knee attached gyroscope gave the closest to the true distance values over three walking conditions. The error from the waist attached accelerometer was the largest. The results from the foot attached accelerometer gave the more errors than knee but less than the waist configuration.

Comparison of three different sensor locations show that the estimate of the heading angle with waist attached gyroscope and distance estimate with the knee attached gyroscope gave the best combination for the personal navigation system.

The higher (body) the inertial sensor is positioned, the less information is obtained. This is the reason why a waist attached accelerometer did not give good results. However, on the other hand, the lower (body) the sensor is attached, the larger the noise it receives. That is because the lower body, experiences larger amount of vibrations during the movement. The foot attached sensor suffered the most from this error. If the accelerometer is attached to the foot, the measurements will include the vibration noises. Based on the test results, the following conclusions are drawn:

- The waist attached accelerometer has relatively large error of 12.5% in distance estimation, however, the waist attached gyroscope gave relatively small heading angle error with the relative error of 0.5%.
- The knee attached gyroscope performed the best with the distance traveled relative error of less than 1%. But it is not suitable for heading angle calculation with a error of 39%.
- The foot attached accelerometer is better than waist attached accelerometer but worse than the knee attached gyroscope in the distance calculation with a percent error of 5%. It is also not suitable for heading angle calculation with a percent error of 45 %.

After comparing these three methods, the optimal personal navigation system has been proposed: A knee attached gyroscope for the distance estimation and another gyroscope at the waist for the heading information.

VII. PROPOSED PERSONAL NAVIGATION SYSTEM

The gyroscope at the knee and waist gave the best performance, so here we use that configuration for personal navigation. A gyroscope collects the movement information from a person's waist provided the heading D, and another gyroscope at the knee provided the distance traveled D. Then these D are transferred to a laptop wirelessly, where a D fusion and parameter estimation are processed to determine the position of the walking person.

7.1 Position Tracking

The distance and heading angle are combined here in order to estimate a person's position in terms of x and y coordinates on a *xOy* plane, where the origin *O* is defined as the point where the person initially stands. The *y-axis* is defined as the direction which the person initially faces, i.e., the person faces the *positive y-axis* and the right-hand side is the *positive x-axis* (Figure 9).

Let i be the serial number of strides, given each stride length $S(i)$ and the heading angle of each stride $\theta(i)$, the position of a walking person can be determined by

$$\begin{cases} x(i+1) = x(i) + S(i+1) \times \sin(\theta(i+1)) \\ y(i+1) = y(i) + S(i+1) \times \cos(\theta(i+1)) \end{cases} \tag{6}$$

where $x(0) = y(0) = 0$, and $L(0) = 0$, $\theta(0) = 0$. The units are in meters and degrees. Figure 9 shows an example of position tracking. The initial position of the walking person is (0, 0), after the first stride, there is 0 degree in change of the heading angle, as a result, the new position after the first stride is (0, 0.923). Then the heading angle change into θ at the end of the second stride**,** using Eq. (6), the updated position is (-0.1249, 1.753).

The position tracking of a walking person follows the proposed algorithms. The proposed system continuously calculates and updates the person's position using the raw D from gyroscopes attached to human body.

7.2 Experimental Results

In order to verify the system for indoor applications, a series of experiments have been performed. The same paths as the previous experiments were selected to evaluate the accuracy of estimated results. Since the distance and heading information are both collected, the goal of tracking a walking person is achieved. A gyroscope was attached to the waist and another gyroscope was attached around the knee of a walking person. The navigation solution was completely based on these sensors. Figure 10 presents the original trajectory and the tracked trajectory. The position error is defined as the distance between the true end and the calculated end. Based on the previous experiment results in Table 1, the walking speed and the stops have little impact on the final result. So the same conditions were applied to all of twenty trials.

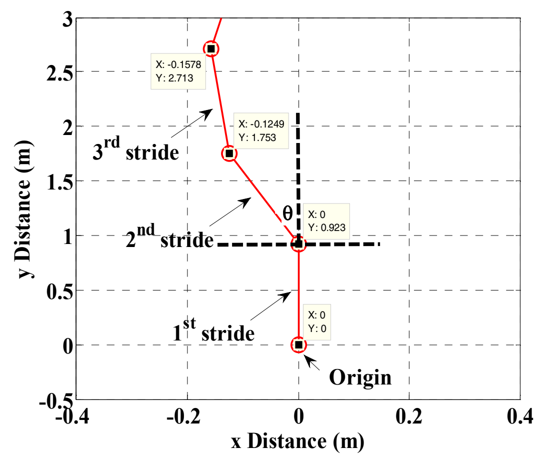

Figure 9 Position of a walking person

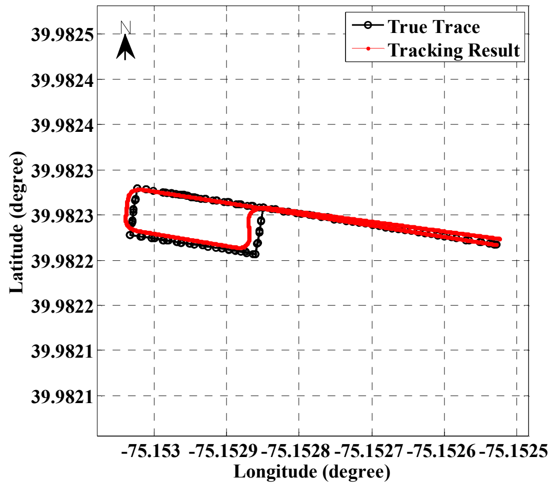

Figure 10 Original trajectory and the tracking trajectory

Twenty trials were performed by a walking person with the start position on the right hand side of the diagram (Figures 10). The experimenter walked through a straight corridor, then made four perpendicular turnings along a rectangle, finally returned to the straight corridor to the end point (i.e. the same point as the start position). The total distance traveled was 96.18m, and the total steps were around 130. Figure 10 shows the results. The percent error between the true steps and measured steps is around 0.77%. The percent error between the true distance and the measured distance is from 0.01% to 3.69%. The average absolute position error is 1.25m with a standard deviation 0.7158m. The average relative position error is 1.59%.

VIII. CONCLUSIONS

Based on a person's navigation analysis and experiments of three different configurations, the design of a novel low-cost personal navigation system with two gyroscopes was discussed. We determined that a gyroscope near the knee gives the optimal distance traveled D and a gyroscope at the waist gave the optimal heading D. The proposed system takes advantage of the fact that the angular displacements repeats with each step and integrating the angular displacement separately at each period keep the angular displacements errors bounded. The system performance was evaluated indoors. The experimental results showed that integration of two gyroscopes in personal navigation system can provide better position estimation and tracking while keeping the cost down. The proposed personal navigation system has the potential to be used in many indoor settings including climbing stairs.

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