Sensor Fusion and Error Compensation Algorithm for Pedestrian Navigation System

Seong Yun Cho*, Chan Gook Park**, and Hwa Young Yim*

* Department of Control and Instrumentation Engineering, Kwangwoon University, Seoul, Korea
(Tel : +82-2-880-1732; E-mail : Syuni@shinbiro.com)
**School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea
(Tel : +82-2-880-1675; E-mail : chanpark@snu.ac.kr)

Abstract: This paper presents the pedestrian navigation algorithm and the error compensation filter. The pedestrian navigation system (PNS) consists of the MEMS inertial sensors, the fluxgate, and the small-size GPS receiver. PNS calculates the navigational information using the signal patterns of the accelerometers. And the navigational information is completed by integration of the patterns, the fluxgate, and the GPS information. In general, PNS can provide the better solution than the low-cost inertial navigation system.

Keywords: pedestrian navigation, step detection, step length estimation, azimuth calculation, PNS/GPS

1. INTRODUCTION

In recent, the navigational techniques for providing the position information of vehicles have been adopted for computing that of a man. The portable personal navigation system has been developed based on the E911 implementation requirements that are reported by the Federal Communications Commission (FCC) in 1996.

First, PNS has been implemented using GPS. GPS is the representative radio navigation system based on satellites and has bounded errors. Therefore, GPS has been utilized in many areas. GPS users may, however, experience restrictions on use of the GPS signals because of signal blockage, interference, or jamming. Therefore, the major problem with GPS is its availability and accuracy in urban environments.

In recent, CDMA's pilot signals are investigated in order to determine the position of the mobile phones. The groundwork for navigation has been laid by developing the positioning techniques such as AOA, TDOA, etc. These techniques can be utilized in a building where cannot receive the GPS signals. However, there are many error sources in the CDMA positioning such as multi-path, NLOS, near-far problem, repeater problem, etc. So far, it cannot provide the position information as exact as GPS because of these error sources.

INS is the typical dead reckoning (DR) system using the inertial sensors such as gyros and accelerometers. In recent, MEMS technology allows production of inexpensive, small-size and lightweight inertial sensors. These are all desired properties for components to be used in the personal navigation system. The quality of the MEMS inertial sensors, however, is low conspicuously. A new algorithm is necessary in order to enhance the performance of the personal navigation system implemented using the MEMS inertial sensors. The technical limit and the necessity led the development of the algorithm for PNS. The main idea of PNS is that : The walking distance is calculated by the estimated step length. And position can be computed by integration of the walking distance and the azimuth information.

Recently various systems and algorithms for PNS have been introduced. The most of the proposed methods utilize accelerometers. And the operation of PNS algorithm can be divided into three parts : step detection, step length estimation and azimuth calculation. Using physiological models and advanced algorithms it would be possible to implement PNS. First, the step detection can be achieved by the peak detection [1,2,3], zero crossing detection [4,5], and flat detection [6]. Second, step length can be estimated via the stride model expressed by linear combination [2,3,4], the walking speed model [7,8], and double integration of accelerations [6,9,10]. Finally, the azimuth can be calculated using gyros [5,7] or magnetic compass [1,5,10].

In this paper, the steps are detected by flat detection using the acceleration differential and the sliding window summing of the differential signals. This technique is robust against to the walking patterns, road conditions, etc. The step length is estimated using the neural network. This network considers the ground inclination in order to enhance the performance of the step length estimation. And the azimuth is calculated using the 2-axis fluxgate whose tilt error is compensated using the accelerometers and the tilt compensation algorithm.

The error of PNS increases with time because PNS is the DR system like INS. Therefore, the error must be compensated by filter, periodically. The filter is implemented using the Kalman filter, and the GPS measurement.

In order to confirm the performance of the proposed algorithm, a PNS is implemented and the actual walking test is executed. The PNS consists of a 2-axis accelerometer, a 2-axis fluxgate, and a GPS receiver. PNS test is carried out for the known trajectory. And then the saved data is processed with the proposed algorithm and the error compensation filter.

2. PNS ALGORITHM

DR for vehicles is a satisfactory technology. A similar approach is, however, difficult to adopt for PNS. The problems are the sensor configuration, the walking dynamics, and the inherent systematic errors present in MEMS inertial sensors. These problems can cause the non-permissible position errors. Such characteristics do not allow one to compute his position by double integration of the acceleration. An alternative is to use the accelerometer signal pattern rather than its value. Considering the estimated step length, multiplying it by the number of steps detected by the accelerometer signal pattern provide the walking distance. Therefore, the precision of the position is directly influenced by the quality of these parameters. The position error caused by the step length errors is less than that caused by the bias errors of the inertial sensors in INS. Therefore, PNS is better than INS for human navigation.

Figure 1 shows a main algorithm for calculating of the navigation information in PNS. The estimated step length is combined with the azimuth information in order to calculate the current position.

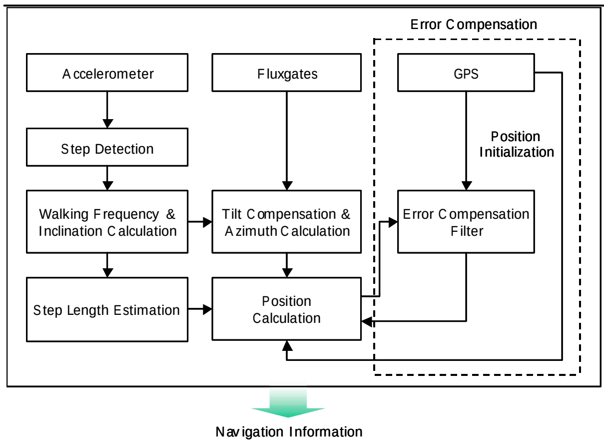


Fig. 1 Block diagram of a PNS algorithm.

2.1 Step detection

The existing pedometer uses a spring-loaded mechanical pendulum to detect the step. The step is detected by sensing the up-down motion of the pendulum. However, the extra bounces of the pendulum can occur because of the mechanical structure. And the pedometer requires manual calibration, is unreliable, and cannot be interfaced to a computer [2].

Recently, the step detection methods using accelerometers have been presented in PNS investigation. Several detection strategies presented in the introduction are possible, but this paper presents one that is robust to the walking environment. This method detects the points of the stance phases.

The accelerometer attached on the shoe is influenced by the acceleration of gravity as well as foot acceleration. The gravity effect can be affected by the ground inclination and the misalignment of the accelerometer even during stance phases. And this effect varies according to time and situation. Unless this effect is eliminated, errors can be caused in the step detection. This effect, however, cannot be removed when the attitude information of the foot is unknown. In this paper, acceleration differential technique is utilized in order to eliminate the acceleration of gravity and detect the stance phase exactly [6]. Eq. (1) denotes the accelerometer output at time t.

$$a_o(t) = a_f(t) + a_g(t) \qquad (1)$$

where a_o means the accelerometer output, a_f denotes the foot acceleration, and a_g is the acceleration of gravity.

The foot acceleration is zero during stance phase. Moreover, the acceleration of gravity does not vary over this duration. Therefore, the gravity effect can be eliminated through the acceleration differential as follows.

$$\Delta a_O(t) = a_O(t) - a_O(t-1) \cong 0 \qquad (2)$$

Therefore, the steps can be detected using the condition that the acceleration differential is small than the threshold that is established via experiment. However, the condition may be occurred during swing phase, occasionally. This phenomenon can arise because foot acceleration is about zero at the intersection of acceleration and deceleration of foot. Therefore, two steps may be detected during one step. In order to remove this phenomenon, following sliding window summing technique is utilized.

$$SWS(t) = \sum_{k=t-N+1}^{t} \Delta a_O(k) \qquad (3)$$

where SWS denotes the sliding window summing, and N means the window size that is established to be less than duration of stance phase.

The SWS s are still exist in the neighborhood of zero during stance phase. However, the sections that are correspond to Eq. (2) during swing phase may be disappeared because the phase size is less than N generally. Therefore, the probability of double step detection in one step decreases through the following process.

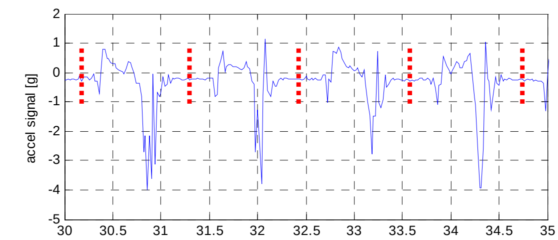
i) $Num = 0$

ii) if $|SWS| < \delta_{SP}$ than $Num = Num + 1$

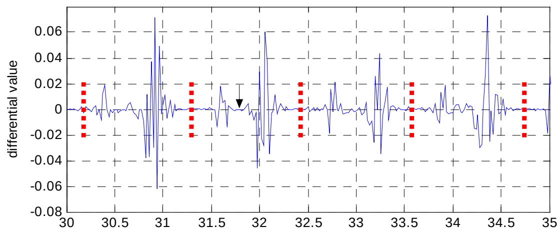
iii) if $Num > num_{SP}$ then this time is stance phase

where δ_{SP} is the threshold for detection of stance phase and is num_{SP} is the number selected properly via experimental process.

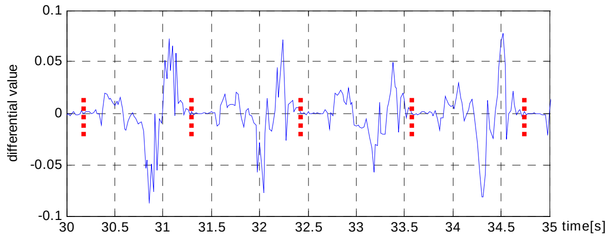
Figure 2(a) denotes the accelerometer signal. This signal has gravity effect because the signal value is not zero during stance phases. Figure 2(b) shows the accelerometer signal differential. It can be confirmed that the differential values during stance phases are almost 0. The similar phenomenon during swing phase, however, can be occurred as a point with an arrow. Because of this fact, steps can be detected twice over one step. In order to overcome this problem, the differentiated values are summed over the sliding window established previously. In result, the flat area close to 0 appears only on the stance phase as figure 2(c).



(a) Accelerometer signal



(b) Differential of (a)



(c) Sliding window summing of (b)

Fig. 2 Signal processing for step detection.

2.2 Step length estimation

A step length that is utilized in order to calculate the walking distance in PNS is the moving distance of the foot over swing phase. If the step lengths are constant, the walking distance can be calculated with accuracy. However, the step lengths vary continuously according to the walking speed, ground inclination, etc. Unless the varied step lengths are considered, the results of PNS may have large errors.

According to the result of our investigation, the step length is influenced by the walking frequency, the variance of the accelerometer signals during one step, the ground inclination, etc. It is presented that the step length is proportional to the walking frequency and the variance in the references [1,2,3,4,5,6]. However, it is confirmed that the step length has complex tendency in the inclination from our investigation. Therefore, the step length cannot be determined by the linear combination suggested in the previous works [2,3,4]. In this paper, the step length is estimated using a neural network in order to consider the various environments.

The proposed neural network is shown in figure 3. the learning for weights and biases is performed using the back-propagation algorithm. The inputs for the neural network are the walking frequency, the variance of the accelerometer signals, and the inclination. These parameters are obtained as

$$f(t_k) = 1/(t_k - t_{k-1}) \tag{4}$$

$$Var(t_k) = \sum_{t=t_{k-1}}^{t_k} \frac{(a(t) - \bar{a}(t_k))^2}{n} \tag{5}$$

$$\theta(t_k) = \sin^{-1}(\hat{a}(t_k)/g) \tag{6}$$

where

$f(t_k)$: walking frequency at t_k

$Var(t_k)$: variance of the accelerometer signals during one step

$\theta(t_k)$: ground inclination

t_k : detecting time of the k -th step

$a(t)$: accelerometer signal

$\bar{a}(t_k)$: average of the accelerometer signals during one step

n : number of the accelerometer outputs during one step

$\hat{a}(t_k)$: average of the accelerometer signals during stance phase

The neural network is pre-learned during a pre-calibration stage and then on-line step lengths are estimated during a use stage. When the GPS signal is reliable, the step length of a pedestrian can be calculated using the position information. The weights and biases of the neural network are learned using the average step length information. The proposed neural network allows to obtain the step length information as figure 4 .

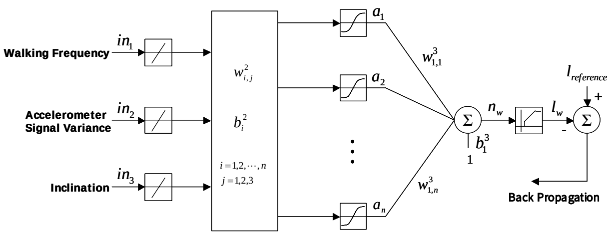


Fig. 3 Neural network for step length estimation.

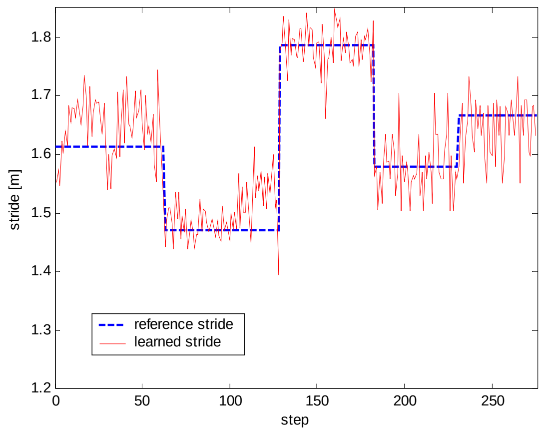


Fig. 4 Step length estimated by the neural network.

2.3 Azimuth calculation

The azimuth is integrated with the step length in order to calculate the current position. In this paper, the azimuth is calculated using a 2-axis fluxgate. The fluxgate calculates the azimuth by measuring the earth magnetic field. Therefore, it has bounded error unlike a gyro. However, the error may include the bias error occurred by the surrounding magnetism and the tilt error. Generally, the fluxgate module consists of three fluxgate sensors and two inclinometers that measure the roll angle and the pitch angle. In this paper, however, the 2-axis fluxgate, and a 2-axis accelerometer are used.

When the tilt angle of the fluxgate exists, the tilt angle can be compensated using the 3-axis fluxgate data and the tilt angle information generally. When only 2-axis fluxgate, however, is utilized, the conventional tilt compensation algorithm cannot be usable. Therefore, this paper utilizes the 2-axis fluxgate tilt compensation algorithm developed in our investigation. Eq. (7) is the tilt compensated azimuth.

$$\psi = \tan^{-1}\left(\frac{-Y_h}{X_h}\right) \tag{7}$$

where X_h and Y_h mean the fluxgate outputs transferred to the horizontal frame. In this process, the roll angle, the pitch angle and the dip angle are necessary. The dip angle can be calculated by the latitude information. And the tilt angle can be obtained using the 2-axis accelerometer as

$$\theta = \sin^{-1}(a_x / g) \tag{8}$$

$$\phi = \sin^{-1}(a_y / g\cos\theta) \tag{9}$$

where a_x and a_y mean the outputs of the accelerometer.

When the inclination of the fluxgate is calculated using the accelerometer attached on the shoe, the data only during the stance phase is utilized. Therefore, the inclination and the azimuth are calculated at the point of time when the step is detected. Figure 5 shows the outputs of the 2-axis fluxgate. The azimuth can be calculated using the complex fluxgate signals during stance phases. Figure 6 denotes the calculated azimuth without tilt compensation. The reference azimuth is calculated by reliable GPS signals. It can be seen that the tilt error is caused such as bias error. However, the tilt error can be compensated using the proposed algorithm as figure 7.

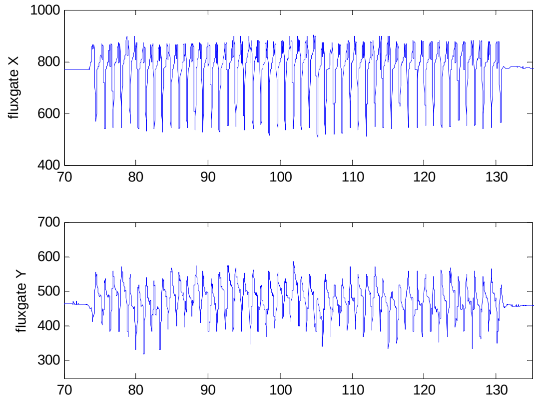


Fig. 5 Fluxgate signals.

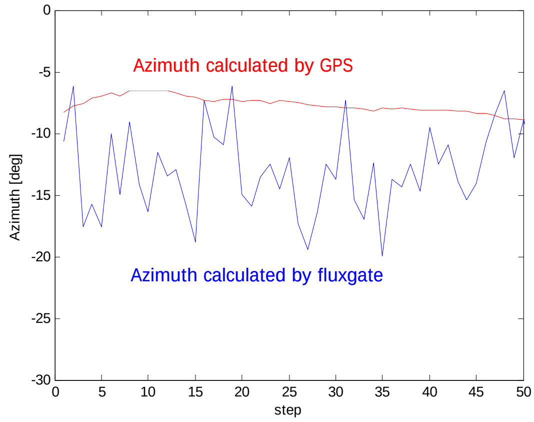


Fig. 6 Azimuth without tilt compensation.

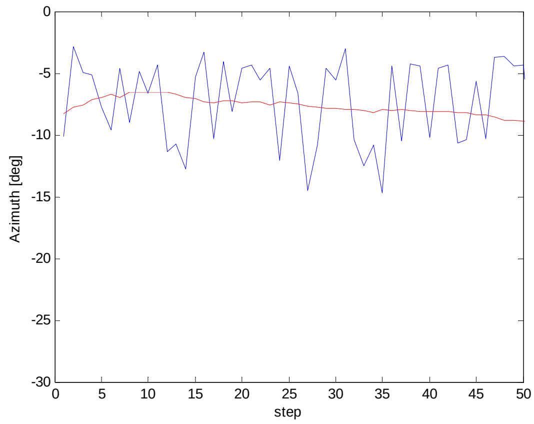


Fig. 7 Azimuth with tilt compensation.

3. ERROR COMPENSATION

The navigation information of PNS has errors that are increased with time because PNS algorithm has the DR structure. There are error sources in PNS such as the estimation error of the step length, the fluxgate bias, the walking frequency error, etc. Therefore, the proper error compensation filter is necessary. In this paper, PNS/GPS Kalman filter is implemented. When GPS signal is reliable, this filter can estimate the PNS error. In order to design the PNS/GPS Kalman filter, the PNS error model is necessary. The model used in this paper is constructed by referring to reference [11,12]. The system model for Kalman filter is as follows:

$$\dot{x}(t) = F(t)x(t) + w(t), \qquad w(t) \sim N(0,Q) \tag{10}$$

where the states of the Kalman filter are position error, velocity error, azimuth error, and step length error.

$$F(t) = \begin{bmatrix} 0_{2\times2} & I_{2\times2} & 0_{2\times1} & 0_{2\times1} \\ 0_{2\times2} & 0_{2\times2} & F_{va} & F_{vs} \\ 0_{1\times2} & 0_{1\times2} & 0_{1\times1} & 0_{1\times1} \\ 0_{1\times2} & 0_{1\times2} & 0_{1\times1} & 0_{1\times1} \end{bmatrix} \tag{11}$$

$$F_{va} = \begin{bmatrix} -\dot{s}\sin\psi - s\dot{\psi}\cos\psi \\ \dot{s}\cos\psi - s\dot{\psi}\sin\psi \end{bmatrix} \tag{12}$$

$$F_{vs} = \begin{bmatrix} -\dot{\psi}f\sin\psi + \dot{f}\cos\psi \\ \dot{\psi}f\cos\psi + \dot{f}\sin\psi \end{bmatrix} \tag{13}$$

where $s = l \cdot f$ is the speed of a pedestrian and l is the step length.

The measurement model is as follows:

$$z(t) = \left[P_{PNS} - P_{GPS}\right] \tag{14}$$

where P_{PNS} and P_{GPS} mean the position information of PNS and that of GPS, respectively.

When PNS is utilized in the urban area, GPS signal is not reliable occasionally. Therefore, it is important that this filter must be utilized when the GPS signal is reliable. Otherwise the quality of PNS/GPS is lower than that of pure PNS.

4. WALKING TEST AND RESULTS

Walking test was conducted in the Seoul National University, Korea in order to confirm the performance of the proposed algorithm and the filter. First, we walked on the appropriate trajectory for pre-learning of the neural network. This trajectory contains flat road, uphill road and downhill road which makes it possible to reflect the effect of ground inclination to the step length estimation. And then the walking test was performed on the trajectory shown in figure 8.

The implemented PNS module was attached on the right side of shoe. And the sensor raw data was logged in the computer memory.

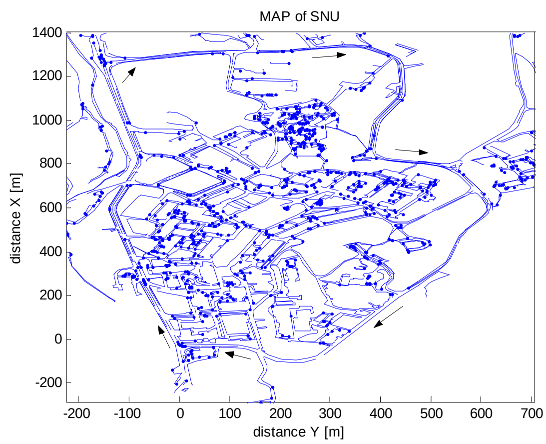


Fig. 8 Trajectory for the walking test.

First, step detection based on the accelerometer signal pattern was performed. And then step length, inclination, and azimuth are calculated at the point of time of stance phase. The number of the walked steps was 2218. And that of the steps detected by the algorithm was 2218 exactly. The steps were detected on the uphill roads and downhill roads as well as flat roads well. Therefore, the performance of the step detection algorithm was confirmed.

Position calculated using the step length and the azimuth is plotted on the digital map. Figure 9 shows the result of the pure PNS. The azimuth calculated using the proposed algorithm is similar with the map. And the calculated positions are plotted on the walked road well before Section A. Figure 10 shows the enlargement of Section A. It can be seen that the azimuth errors are occurred in Section A. an azimuth error of 1 degree will produce a position error of about 2% of traveled distance. Therefore, the calculated position starts to deviate from the trajectory. The error of the position will increase with time unless error compensation is performed.

Figure 11 denotes the result of the PNS/GPS. The filter is performed only in the Section B, C, and D because the GPS signals are reliable in these Sections. The pure PNS is carried out in the except areas of these Sections. It can be seen that almost positions calculated by the proposed algorithm and the filter are on the trajectory. The total distance of the walked trajectory is about 4km. In the walking test, the compensated position error remained below 20m. Therefore, it is confirmed that the performance of the proposed algorithm and filter is good.

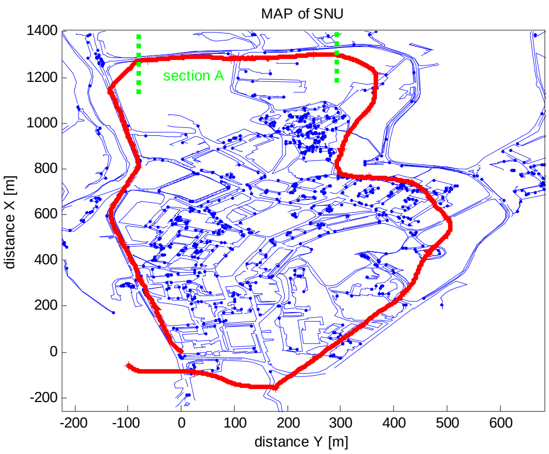


Fig. 9 Result of the pure PNS without GPS.

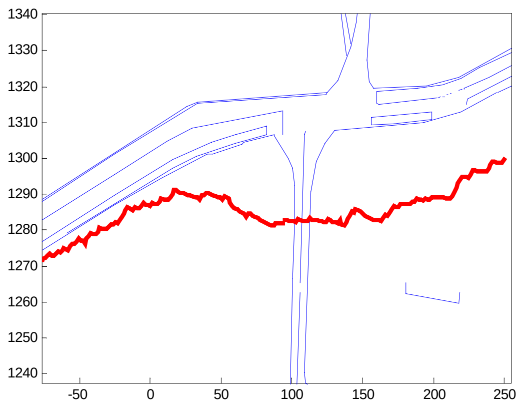


Fig. 10 Enlargement of Section A.

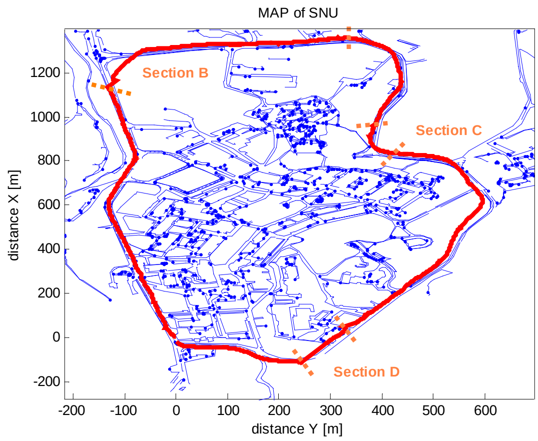


Fig. 11 Result of PNS/GPS.

5. CONCLUSIONS

This research demonstrates the algorithm and the filter for the pedestrian navigation system. The sensors used in this research are one MEMS type 2-axis accelerometer, a low-cost 2-axis fluxgate, and a small-size GPS receiver. The key of the proposed algorithm for PNS is a detection technique of the stance phase. The performance of the proposed step detection algorithm is excellent. The step length and the azimuth are calculated during stances. The step length is estimated using the neural network. And the azimuth is calculated using the algorithm for 2-axis fluxgate. However, the error of PNS increases with time because of the DR structure. In order to compensate the PNS error, the PNS/GPS integrated Kalman filter is designed. The walking test is performed in order to confirm the proposed algorithm and the filter. Results show that PNS/GPS with proposed algorithm can extend the positioning availability and accuracy of the navigation system like GPS, INS, etc.

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