

New Map-Matching Algorithm Using Virtual Track for Pedestrian Dead Reckoning

Seung Hyuck Shin, Chan Gook Park, and Sangon Choi

In this paper, a map-matching (MM) algorithm which combines an estimated position with digital road data is proposed. The presented algorithm using a virtual track is appropriate for a MEMS-based pedestrian dead reckoning (PDR) system, which can be used in mobile devices. Most of the previous MM algorithms are for car navigation systems and GPS-based navigation system, so existing MM algorithms are not appropriate for the pure DR-based pedestrian navigation system. The biggest problem of previous MM algorithms is that they cannot determine the correct road segment (link) due to the DR characteristics. In DR-based navigation system, the current position is propagated from the previous estimated position. This means that the MM result can be placed on a wrong link when MM algorithm fails to decide the correct link at once. It is a critical problem. Previous algorithms never overcome this problem because they did not consider pure DR characteristics. The MM algorithm using the virtual track is proposed to overcome this problem with improved accuracy. Performance of the proposed MM algorithm was verified by experiments.

Keywords: Map-matching, PDR, virtual track, pedestrian, dead reckoning.

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Seung Hyuck Shin (phone: +82 2 880 1732, email: mad2407@snu.ac.kr) is with the School of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Rep. of Korea.

Chan Gook Park (corresponding author, email: chanpark@snu.ac.kr) is with the School of Mechanical & Aerospace Engineering and the Institute of Advanced Aerospace Technology, Seoul National University, Seoul, Rep. of Korea.

Sangon Choi (email: sangon.choi@samsung.com) is with Samsung Electronics Co. Ltd., Rep. of Korea.

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I. Introduction

The navigation techniques for providing the position information of vehicles can be applied to the navigation of pedestrians. The portable navigation system has been developed based on the Enhanced 911 (E911). The portable navigation system has been implemented using GPS, CDMA's pilot signals, and AGPS/TDOA. However, these techniques have several limits, such as restrictions on the use of GPS signals and many error sources in the CDMA signals. Another research area for the navigation system is the MEMS-based pedestrian dead reckoning (PDR) system. A pedestrian, by definition, can only move by walking. Thus, PDR is based on the step information, and it can be obtained using inertial sensors. The position of the pedestrian can be estimated when the step length and the azimuth are known. PDR is expected to be utilized in both indoor and outdoor environments because it is autonomous and not susceptible to external jamming. Also, the infra network is not required as in other systems.

One of the key difficulties in PDR is estimating the step length. Various systems and algorithms for PDR have been introduced [1]-[9]. The azimuth information has to be synchronized with the step information to calculate the position. In the pedestrian environment, the magnetometer is very useful [7], [10], [11]. It does not have errors which increase with time, unlike gyro-based azimuth information.

A map-matching (MM) algorithm is a method for mapping the estimated position from the navigation system to digital map data. The general purpose of MM algorithms is to identify the correct road segment on which the pedestrian or the vehicle is traveling and to determine the position on that segment. MM algorithms not only enable the physical location to be identified but also improve the positioning accuracy. There are several

existing MM algorithms. White and Quddus proposed some topological MM algorithms [12], [13]. Ochieng developed the probabilistic MM algorithm [14]. Kim [15] and Quddus [16] researched an MM algorithm using fuzzy inference. Zhang [17] researched an MM algorithm using historical information. Shin and Park [18] developed an MM algorithm using DR correction and arc-matching method for PDR. Rafael [19] proposed the data fusing using the particle filter. Beauregard [20] presented the MM algorithm using a particle filter for PDR. Tradisauskas [21] presented an MM algorithm for intelligent speed adaptation. Ren [22] proposed a hidden Markov model-based MM algorithm for wheelchair navigation. Some authors referred to the concept of integrity in MM algorithms [23]–[25].

However, most previous MM algorithms are for the navigation system based on GPS, which is a kind of position-fixing-scheme-based navigation system. Thus, most of the existing MM algorithms are not appropriate for the PDR system, which is a DR-scheme-based navigation system. In this paper, we propose an MM algorithm using a virtual track, making it very efficient for use with the PDR system.

This paper is organized into six sections. The PDR module and the system description are introduced briefly in section II. The PDR algorithms are drawn in section III. In section IV, an MM algorithm using a virtual track is proposed. The performance of the proposed algorithm is verified experimentally in section V. Finally, conclusions are shown in the section VI.

II. System Description

The proposed PDR module consists of a tri-axial accelerometer, three axes gyros, and magnetometers. The components of the system are small-sized and low-cost. These features are important for PDR because PDR is often supposed to be embedded into mobile devices, such as cell phones and PDAs. The data of the sensor module is transferred to a navigation computer through the blue-tooth module.

The PDR module can be attached on the waist, the thorax, or a shoe. In this research, the PDR module is equipped on a



Fig. 1. PDR module.

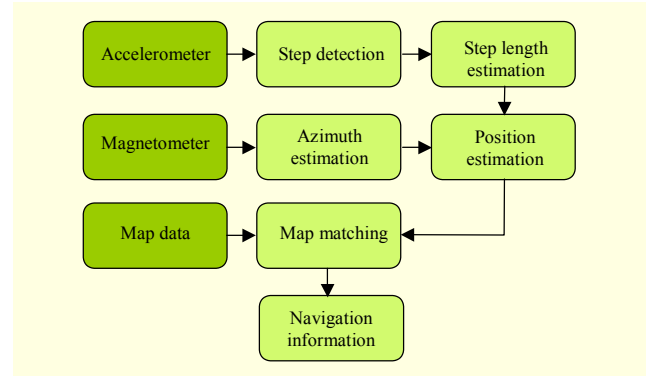


Fig. 2. Block diagram of PDR algorithm.

pedestrian's waist belt. Figure 1 shows the sensor module. The block diagram of the developed PDR algorithm is shown in Fig. 2. The position of the pedestrian is estimated using accelerometers and magnetometers. The walking distance can be obtained by accelerometers. The azimuth can be calculated by magnetometers. Finally, the estimated position and the digital road map are integrated using the MM process.

III. Pedestrian Navigation Algorithm

1. Step Detection Algorithm

Step detection is generally an easy problem in PDR. However, false or missed detections can cause considerable errors in the estimation of a total walking distance. The total walking distance is calculated using the summation of every estimated step length. Recently, step detection methods using accelerometers have been presented in PDR investigation. There are three types of methods: peak detection, zero crossing detection, and flat zone detection using an acceleration differential. The peak detection method is not appropriate to detect steps because the peak of the accelerometer output is greatly affected by the walking velocity. The flat zone of the signal is not detected when the accelerometer is attached to the pedestrian's waist belt. Thus, the pedestrian's step is detected using the zero crossing method which is resilient to the pedestrian's walking velocity.

The accelerometer, which is attached to the body, is influenced not only by the acceleration of the body but also noise and other factors such as the bias of the accelerometer and gravity. In order to remove the noise from the output of the accelerometer, the signal is summed over the sliding window established previously. The signal is differentiated to eliminate various error sources, such as the bias of the accelerometer and gravity. The zero crossing point of the output of the accelerometer is detected using this signal. The experimental result of the step detection algorithm is shown in Fig. 3. The

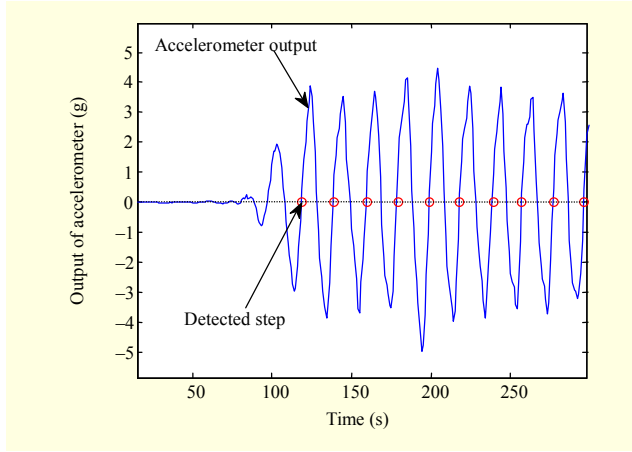


Fig. 3. Step detection using zero crossing detection method.

blue line stands for signal processed acceleration and the red circles are detected steps.

2. Step Length Estimation Algorithm

According to the result of our investigation and previous papers, the step length is influenced in the linear pattern by a walking frequency and a variance of the accelerometer signals during each step. Thus, we can determine the step length using a linear combination of walking frequency and acceleration variance as

$$\text{Step length} = \alpha \cdot WF + \beta \cdot AV + \gamma, \quad (1)$$

$$WF = 1/(t_k - t_{k-1}), \quad (2)$$

$$AV = \frac{1}{n-1} \sum_{i=1}^n (a_k - \bar{a})^2, \quad (3)$$

where α , β , and γ are the parameters pre-learned during a pre-calibration stage. WF and AV denote the walking frequency and acceleration variance, respectively.

The total walking distance is obtained by

$$\text{Walking distance} = \sum_{i=1}^n (\alpha \cdot WF_i + \beta \cdot AV_i + \gamma), \quad (4)$$

where n denotes the total number of occurred step.

3. Azimuth Calculation

The walking direction in PDR is needed to estimate the position. The azimuth is the angle between north and the moving direction. One of the techniques for measuring the azimuth is to use the magnetometer. When the tilt angle of the magnetometer exists, the tilt error in the azimuth occurs. Generally, the magnetometer module consists of three magnetometer sensors and two inclinometers in order to

compensate the tilt error. The three axes magnetometers must be mutually orthogonal in the Cartesian reference frame. The azimuth is calculated using the normalized output of the magnetometer as

$$\psi = \tan^{-1} \left(\frac{-Y_m \cos \phi + Z_m \sin \phi}{X_m \cos \theta + Y_m \sin \theta \sin \phi + Z_m \sin \theta \cos \phi} \right), \quad (5)$$

where X_m , Y_m , and Z_m denote outputs of magnetometers. A roll angle and a pitch angle are denoted by ϕ and θ , respectively.

IV. Map-Matching Algorithm Using Virtual Track

1. Map-Matching Algorithm

The MM algorithm is a method for mapping the estimated position from the navigation system to digital map data. Generally, the MM algorithm enables the user to identify the physical location. The estimated position from the navigation system is represented by numerical coordinates. The MM algorithm provides the user with the physical location, not coordinates. The MM algorithm also improves the positioning accuracy. Figures 4 and 5 show the principle concept of the MM algorithm. Figure 4 shows the actual position of the pedestrian in the real world. The estimated position and map-matched point are shown in Fig. 5. Every road in the real world is represented as a set of links in the digital map. The estimated position obtained from the navigation system cannot be placed on the link. In this situation, the MM algorithm can be used to match the position onto the correct link, assuming that the pedestrian walks on the road.

The procedure of MM algorithms is shown in Fig. 6. The MM algorithm scans the candidate links derived from the given map data and the estimated position. The MM algorithm is classified by how candidate links and the final link are determined. Several types of MM algorithms are introduced in section I. In this paper, we used the general topological MM

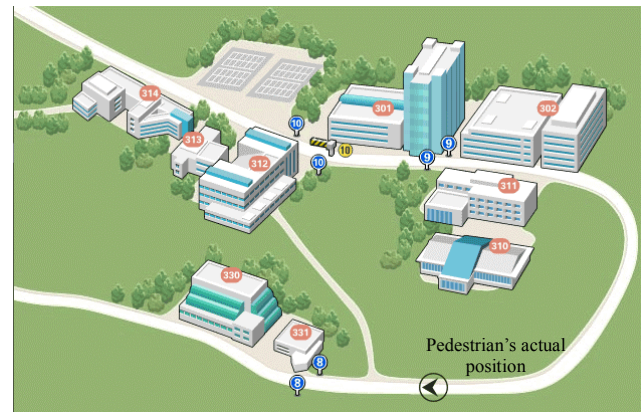


Fig. 4. Actual position of pedestrian.

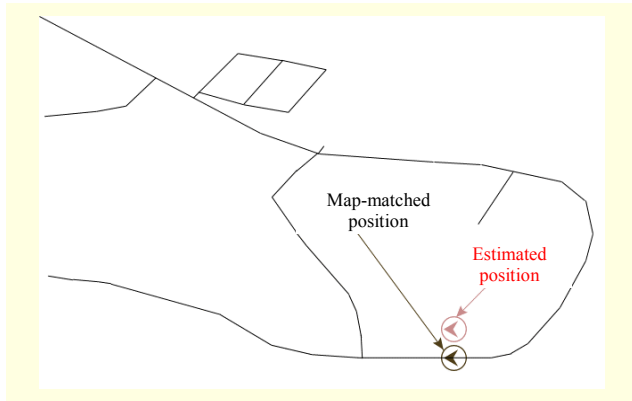


Fig. 5. Estimated position and map-matched position.

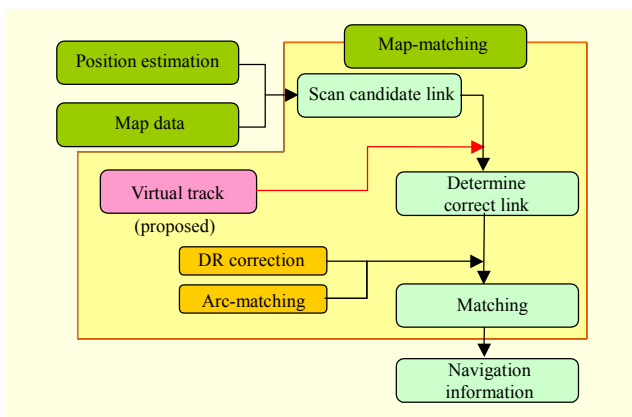


Fig. 6. Block diagram of MM algorithm using virtual track.

algorithm. Candidate links are determined by the distance between the estimated position and link. When the calculated distance is small enough, the link is recognized as a candidate link. The final link is determined by the heading difference between the estimated heading of the pedestrian and the heading of candidate links. The link with the smallest heading difference is determined to be the final correct link. After the correct link is determined, the estimated position is matched on the final link. The distance d between the estimated position and the candidate link is calculated as

$$d = \frac{|ax_p + by_p + c|}{\sqrt{a^2 + b^2}}, \quad (6)$$

where x_p and y_p are the coordinates of the estimated position, and a , b , and c are the coefficients of the link equation ($ax+by+c=0$).

The heading difference ($\Delta\psi$) between the azimuth of the pedestrian and the heading of the candidate link is calculated as

$$\Delta\psi_i = \psi_{\text{pedestrian}} - \psi_i, \quad (7)$$

where ψ_i is the heading of the i -th link.

It is not easy to develop an MM algorithm for a pedestrian.

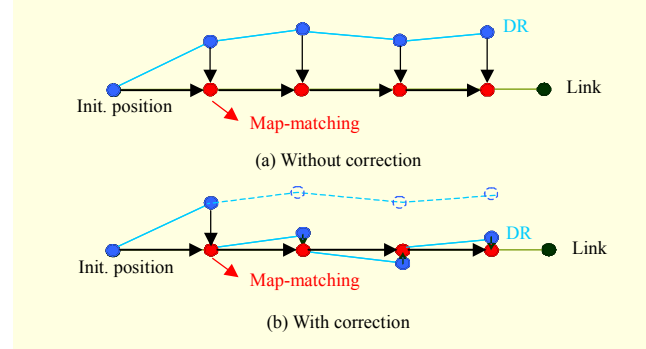


Fig. 7. DR correction method.

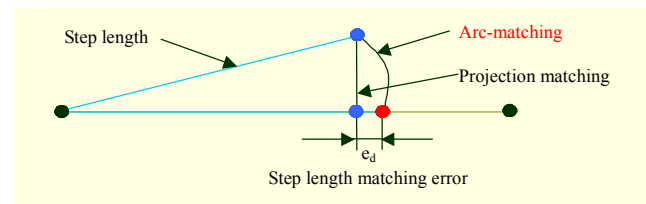


Fig. 8. Arc-matching method.

The performance of an MM algorithm depends on the accuracy of the navigation system and the digital map data. If the estimated position and the digital map are very accurate, the execution of the MM algorithm becomes very straightforward: the positioning data is matched to the nearest road. However, accurate positioning data and network data may not be available in the real world. Most of the existing digital maps, however, are for the car navigation system. The pedestrian is even expected to walk on the branch, which is not described in the digital map. Existing digital maps are not accurate enough to be used to design an MM algorithm for PDR. In this paper, the common digital map was used. It is assumed that the pedestrian walks only on the main road and not on branches.

Most of the previous MM algorithms are for the GPS-based navigation system, which is a position-fixing-scheme navigation system. GPS does not need a previously estimated position to estimate the present position. PDR, however, is a navigation system based on DR. The present position is estimated by propagating the previous estimated position. This means that most of the previous MM algorithms cannot be used for PDR.

The DR correction method and the arc-matching method were developed for the MM algorithm for PDR. DR correction and arc-matching are needed to match the estimated position with the final link, as shown in Figs. 7 and 8. These methods can enhance the performance of the MM algorithm for PDR [16].

The biggest problem of the DR-based MM algorithm is that the MM algorithm cannot determine the correct link when the MM algorithm fails to determine the correct link during the

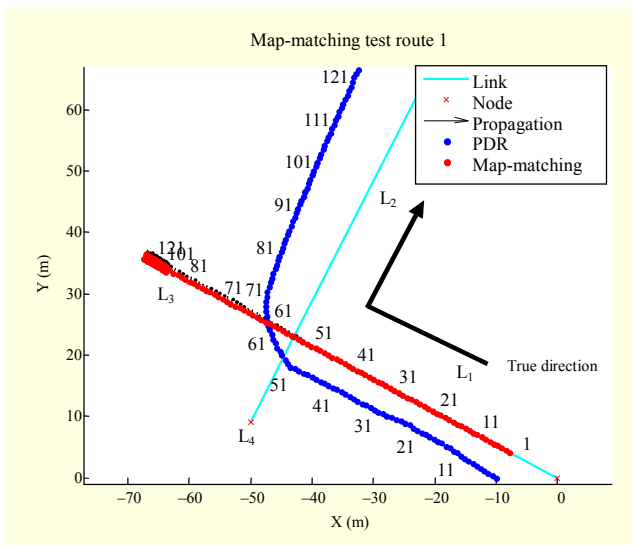


Fig. 9. Most serious problem MM result.

previous step. This problem is shown in Fig. 9, and it can occur at a crossroad or a branch road when the estimated position is not accurate. The true links are link 1 and link 2 in Fig. 9. The MM algorithm, however, does not select link 2 at the crossroad (step 54) because the heading of the pedestrian is changed smoothly even at an orthogonal trajectory like a crossroad. The PDR estimates the present position from the previously estimated position. For these reasons, the map-matched point is still placed on link 3 after step 56. The MM algorithm cannot cover every possible error. This paper focuses on the solution to this problem. In order to overcome this problem, we propose the MM algorithm using a virtual track.

2. Virtual Track

Among the candidate links, the final link is determined using the heading difference between the estimated azimuth of the pedestrian and the heading of the link. The link which has the smallest heading difference is the final link. However, when there is a strong likely candidate link that yields a small enough heading difference, the MM algorithm is supposed to calculate the virtual track with respect to this candidate link until the MM algorithm can confirm the true correct link. When the map-matched trajectory using the final link is not correct, the MM algorithm decides that the virtual track with respect to the strong likely candidate link is correct.

Figure 10 shows the procedure of the MM algorithm using the virtual track. The map data consists of nodes (n_1 through n_{10}) and links (L_1 through L_9). The blue dotted arrow denotes the trajectory of the pure PDR. The red arrow denotes the trajectory of the MM algorithm. And the black circle denotes the virtual track.

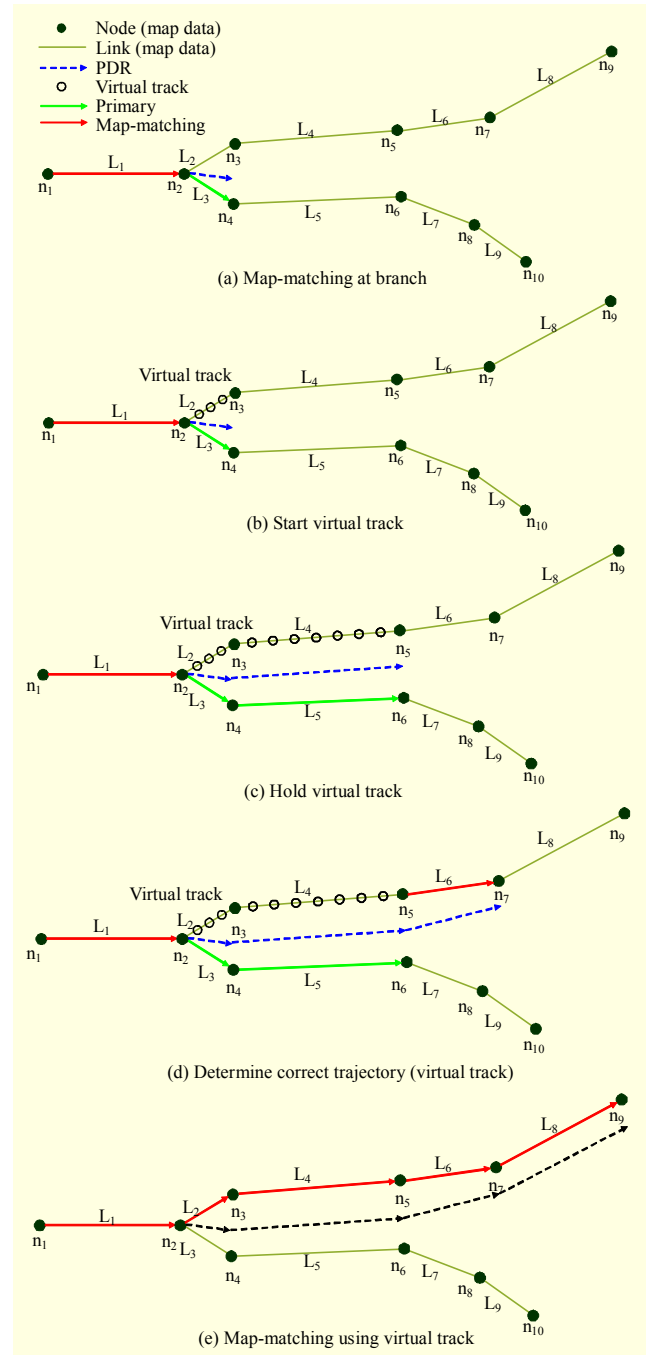


Fig. 10. Procedure of MM using virtual track.

It is assumed that the pedestrian walks on $L_1 \rightarrow L_2 \rightarrow L_4 \rightarrow L_6 \rightarrow L_8$. Candidate links can be L_2 and L_3 at n_2 in Fig. 10(a). The final link is L_3 (primary) because the $\Delta\psi_3$ is smaller than $\Delta\psi_2$. However, the $\Delta\psi_2$ is small enough (that is, below 30° considering the heading error of magnetometers and the misalignment angle between magnetometers and the true pedestrian heading) for consideration as the final link. Thus, the proposed MM algorithm computes the virtual track with respect to L_2 in Fig. 10(b). It is assumed that there is only one

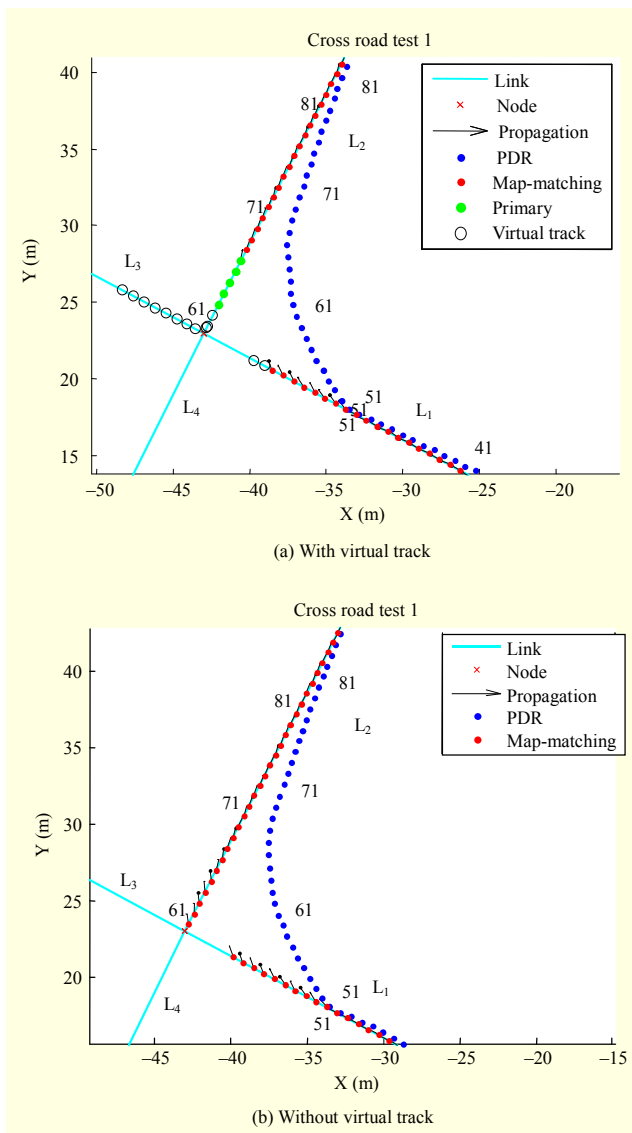


Fig. 11. Simulation result (when result of PDR is good).

computed virtual track in this paper. In Fig. 10(c), the proposed MM algorithm holds to compute the virtual track because $\Delta\psi_4$ is similar to $\Delta\psi_5$. In Fig. 10(d), considering of the trajectory of PDR, the correct link is not L_7 but L_6 because $\Delta\psi_6$ is much smaller than $\Delta\psi_7$, which is over 30° .

The DR-based MM algorithm does not use the virtual track, and the MM algorithm never returns to the correct link in this case. Thus, the proposed algorithm matches the estimated position to L_6 . This means that the MM algorithm recognizes that the virtual track is true in Fig. 10(e). The primary map-matched trajectory is not true. The computing burden of the proposed algorithm can be increased. The proposed algorithm, however, is necessary and works efficiently with the DR-based navigation system.

Figures 11 and 12 show the simulation results of the

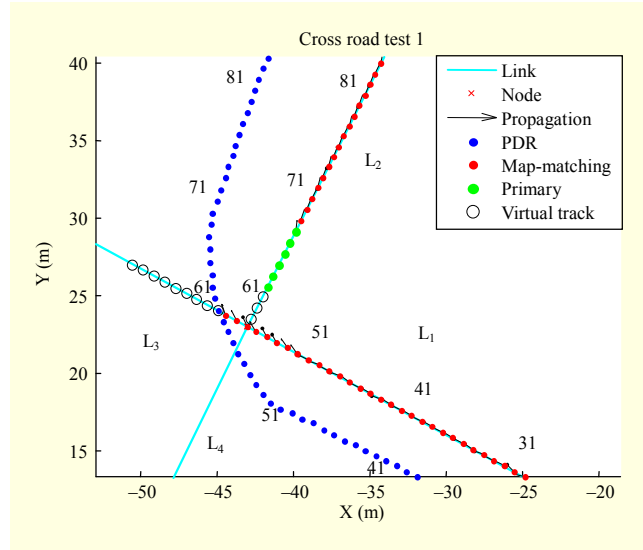


Fig. 12. Simulation result (when result of PDR is bad).

proposed algorithm. It is assumed that the pedestrian walks on $L_1 \rightarrow L_2$. The simulation result of a good PDR trajectory is shown in Fig. 11(a). The virtual track with respect to L_1 , L_2 , and L_3 was computed for steps 59 through 67. This is why the estimated heading of the pedestrian is varied smoothly around of the crossroad. A good simulation result was obtained for this case. The digital map data is given. Thus, the performance of the algorithm only depends on the accuracy of the navigation system. The proposed algorithm definitely works well when the performance of the navigation system is good. Even though the MM algorithm does not use the virtual track, the performance of the MM is expected to be accurate, as shown in Fig. 11(b).

Figure 12 shows the simulation result of a very bad PDR trajectory. The result without the virtual track was already shown in Fig. 9. The MM result cannot return to the correct link (L_2). In Fig. 12, steps 54 through 58 were matched on L_3 as the PDR trajectory, even though the virtual track respect to L_2 was computed for steps 54 through 56. The virtual track, however, was computed for steps 59 through 66 with respect to L_3 again. Then the proposed algorithm finally returned to the correct link (L_2). Consequently, there were some false MM results for 5 steps, but the proposed MM algorithm was able to finally determine the correct link (L_2).

V. Experimental Results

Walking tests were conducted at the Seoul National University, Korea, in order to verify the performance of the proposed algorithm. Tests were performed based on the assumption that pedestrians normally walk. Highly non-uniform motions such as sitting, standing, running, or walking

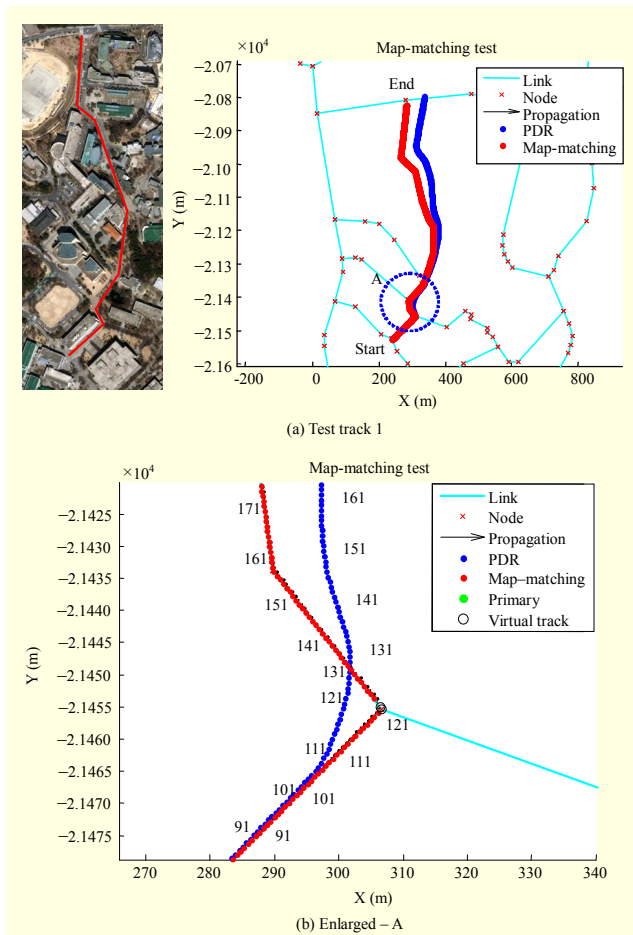


Fig. 13. Experimental results of test track 1.

with a limp or crutches were not considered. The sensor data was logged in the memory of the navigation computer. The sensor data could be seen in the monitor program loaded on a notebook PC. Figure 13(a) shows the test trajectory that was used to verify the proposed MM algorithm.

Figures 13 through 15 show the experimental results of the proposed MM algorithm using the virtual track. Figure 13 shows the result of test track 1. The distance of track 1 was 785 m and 988 steps were detected. Several three-way junctions and the longest test track were used for this paper. The result of the MM without the virtual track was very good because the PDR trajectory of track 1 was good. The position estimation error without the MM algorithm was up to 55.7 m. The error percentage was 7.3% with respect to the total distance. The estimation error with the MM algorithm was 12.4 m. The error percentage was 1.6% with respect to the total distance.

Figure 14 shows the results of test track 2. The distance of test track 2 was 580 m, and 771 steps were detected. There was a parallel road in track 2. False link determination can occur in a parallel road because the headings of two parallel links are

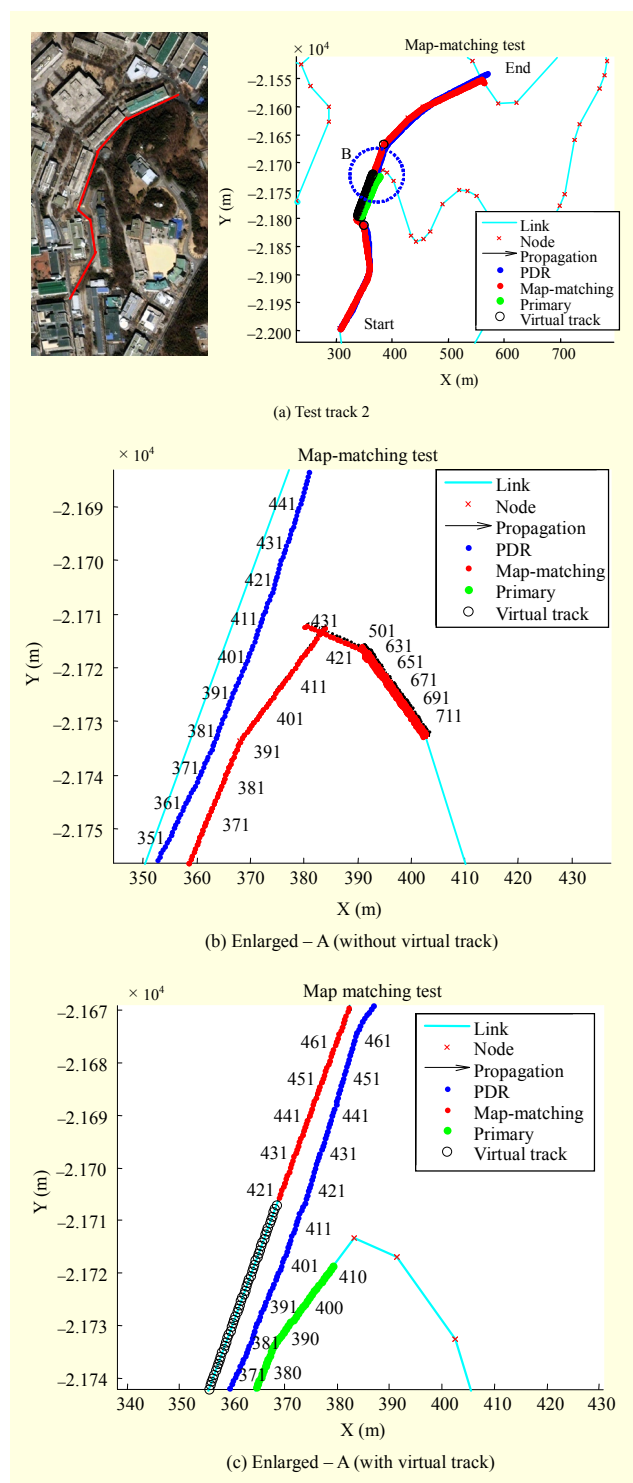


Fig. 14. Experimental results of test track 2.

similar to each other. In Fig. 14(b), the MM result indicates the wrong link because there was a false link determination at the previous step. The proposed MM algorithm can overcome this problem, as shown in Fig. 14(c). The virtual track was computed from step 297 to step 403. At first, the primary

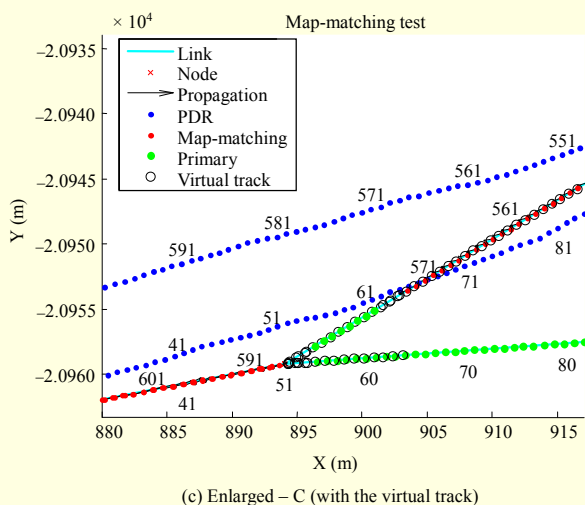
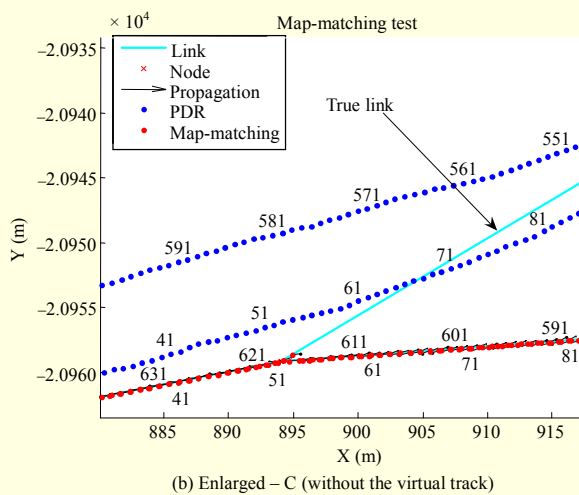
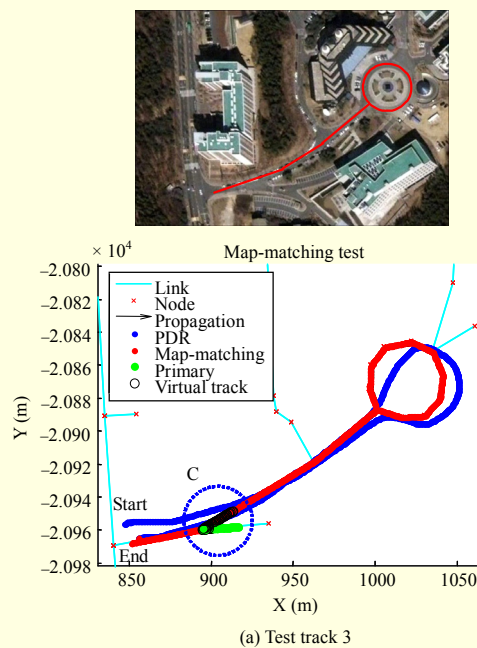


Fig. 15. Experimental results of test track 3.

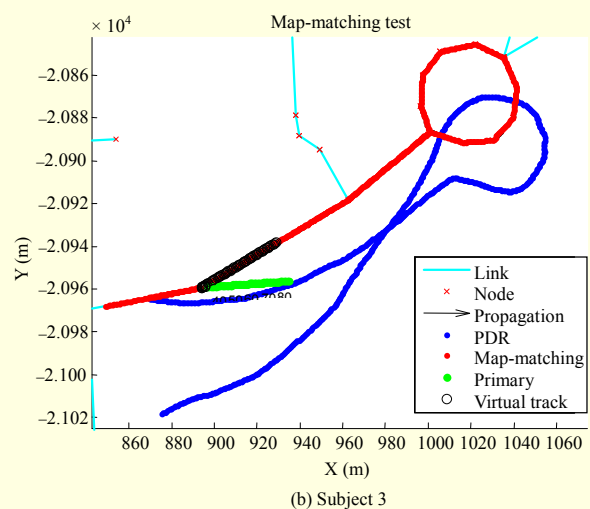
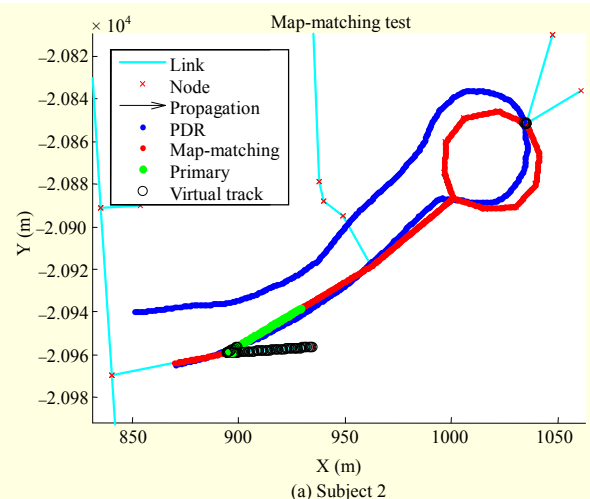


Fig. 16. Experimental results of test track 3.

trajectory (green dotted line) selected the wrong link. The proposed algorithm, however, determined the true link using the computed virtual track after step 403. The position estimation error with the proposed MM algorithm at the last position of the pedestrian was 8.9 m. This is about 1.5% (error percentage) with respect to the total distance.

Figure 15 shows the results of test track 3. The distance of test track 3 was 480 m, and 643 steps were detected. There is a close branch and a circle road in track 3. The start position and the end position of the pedestrian are same. False link determination can occur in an adjacent branch, too. In Fig. 15(b), the MM was able to return to the true link. Figure 15(c) shows the results of the proposed MM algorithm. The virtual track was computed from step 54 to step 105. At first, the primary trajectory (green dotted line) selected the wrong link. The proposed algorithm, however, recognized that the computed virtual track was true at step 105. The virtual track was computed again from step 578 to step 586 to determine the

Table 1. Result of corner trajectory tests.

Result \ MM	Without VT	With VT
Result (success / total tests)	13 / 20	20 / 20

link at the branch when the pedestrian returned. The position estimation error with the proposed MM algorithm at the last position of the pedestrian was 5.7 m. This is about 1.2% (error percentage) with respect to the total distance.

Figures 13 through 15 are results of same subject. The proposed algorithm was tested by the other two subjects on test track 3. Figures 16(a) and (b) are the results of subject 2 and subject 3, respectively. The MM position estimation error at the last position of subject 2 was about 4.7 m. The position error was 5.54 m of subject 3. So, the performance of the proposed MM algorithm is robust to different subjects.

In order to verify the accuracy of the MM with the virtual track, tests were performed 20 times at the same crossroad. Without a virtual track, the success ratio of the MM algorithm was 13/20, while that of the MM algorithm with virtual track was 20/20. Table 1 shows the MM results.

VI. Conclusion

In this paper, a new MM algorithm for the pure DR-based navigation system was proposed. The proposed algorithm uses the virtual track to enhance the accuracy of the MM algorithm for the DR-based navigation system. The biggest problem of the DR-based MM algorithm is that it cannot determine the correct link due to DR characteristics. The proposed algorithm, however, can overcome this problem using a virtual track. When there is a likely candidate link other than the final link, the proposed algorithm computes the virtual track. Then, the MM algorithm can correct the matched trajectory by using the computed virtual track when the previous map-matched trajectory is not true.

Experiments were conducted at Seoul National University, Korea, in order to verify the performance of the proposed algorithm. Experimental results showed that the proposed MM algorithm using a virtual track was very efficient and appropriate for the DR-based navigation system.

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Seung Hyuck Shin is a PhD student in the School of Mechanical and Aerospace Engineering of Seoul National University, Seoul, South Korea. He received his BS in Information and Control Engineering from Kwangwoon University in 2004. He received his MS in the School of Mechanical and Aerospace Engineering of Seoul National University in 2006. His current research interests include the pedestrian dead reckoning, PDR/WLAN integration algorithm, context awareness, inertial navigation systems, and MEMS-based IMU applications.



Chan Gook Park received the BS, MS, and PhD in control and instrumentation engineering from Seoul National University, Seoul, Korea, in 1985, 1987, and 1993, respectively. He worked with Prof. Jason L. Speyer on peak seeking control for formation flight at the University of California, Los Angeles (UCLA) as a postdoctoral fellow in 1998. From 1994 to 2003, he was with Kwangwoon University, Seoul, Korea, as an associate professor. In 2003, he joined the faculty of the School of Mechanical and Aerospace Engineering at Seoul National University, Korea, where he is currently a professor. From 2009 to 2010, he was a visiting scholar with the Department of Aerospace Engineering at Georgia Institute of Technology, Atlanta, GA. He served as a chair of IEEE AES Korea Chapter until 2009. His current research topics include advanced filtering techniques, inertial navigation system (INS), GPS/INS integration, MEMS-based pedestrian dead reckoning, and FDIR techniques for satellite systems.



Sangon Choi is a principal engineer of Digital Media and Communication Business at Samsung Electronics Co., Ltd. His research interests are in human interaction, user interface, and sensing platform technology. He received the ME and DE in electrical and electronic engineering from Toyohashi University of Technology, Toyohashi, Japan, in 1994 and 1997, respectively. In 1997, he joined Samsung Advanced Institute of Technology, Korea.