A Novel Approach for Pedestrian Positioning Using Inertial Sensors

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ABSTRACT

The demand for navigating pedestrian by using inertial sensors increased remarkably over the past few years, especially where Global Positioning System (GPS) is denied, spoofed or blocked by the environmental subjects. In the literature there are many studies aim to overcome specific problems on designing accurate positioning system, however when it comes to design the system in production level -so that can be used in the field for various purposes-, some additional requirements might emerge. In this paper we present an approach of a Zero Velocity Update Detection (ZUPT) algorithm design to analyse one of these requirements: subject invariant estimation consistency.

1.0 INTRODUCTION

For the last two decades, inertial signal-based pedestrian navigation solutions are in the scope of researchers' interests to provide positioning without GPS assistance. The advantage of inertial measurements is that they are possible in many environments and they do not suffer from privacy problems. However, the drift of the inertial signals causes accumulated positioning errors that must be diminished. Zero-velocity detectors (ZVDs) find the static region representing stance phase of a walking gait cycle on a foot mounted Inertial Measurement Unit (IMU) sensors. By detecting the Zero Velocity during stance phase of a gait cycle, the accumulated errors of foot-mounted inertial sensors can efficiently be bounded where the estimation problem is formulated as a Extended Kalman Filter for INS strap down mechanization equations.

Even with the benefit of implementing Zero Velocity Update Detection (ZUPT) in the INS process, it is common knowledge that this framework has unbounded position error growing over time. Surely pace of deviation from ground truth depends on many factors e.g. algorithm developed or quality of inertial sensor, but in anyway, in order to achieve robust, accurate positioning system for field operations, a multi-sensor approach is required in a fusion matter. As stated in [1] INS should be located as the core of a such fusion system. And due to this centralized system approach, INS based navigation performance should be maximized for not only achieving better performance in fusion framework but also for presuming navigation estimation in case of other resources' absence or unavailability for usage under certain conditions. There are many studies in the literature to improve navigation performance such as elimination or mitigation of systematic errors of INS model such as estimation of non-zero velocity components in the detected ZUPT region [2] or g-sensitivity estimation of the gyroscope sensors [3]. Some studies aim to improve heading estimation using angular velocity measurements by using two inertial measurement units (IMU) for both foot and a distance measurement device in order to measure the range between two feet [2]. Such studies show promising navigation performance, but as to our knowledge there is no detailed experimental analysis of this systems.

On the other hand, no matter how an algorithm is designed, usage of this system in the field, brings along additional requirements that designed algorithm should also fulfil. This paper describes our contributions on analysing one these requirements for shoe-mounted inertial sensor navigation: subject invariant navigation consistency in terms of ZUPT design. From our respective, it is convenient way to initiate such core navigation system design that performs consistent on different users and then build additional features to improve positioning accuracy as further actions. To that end we have proposed a robust stance phase detection algorithm to handle both walking and running that also aid navigation performance in consistent way since performance and robustness of ZUPT plays crucial role on navigation accuracy. Magnetometer is used for achieving better heading angle estimation since heading angle is not observable in the nominally LTI system during ZUPT correction in EKF structure.

In this content, this paper is organised as follows. Section 2 describes briefly some requirements for shoe-mounted inertial sensor navigation without considering safety related topics. Section 3 presents stance phase detection importance on navigation performance and how the new approach improves navigation performance for running scenarios. Our approach for the validation of developed initial navigation system for both running and walking is introduced in Section 4 and the paper is concluded in Section 5.

2.0 ADDITIONAL REQUIREMENTS FOR SHOE-MOUNTED INS

As stated before designing shoe-mounted inertial navigation system in such way that can be used in the field, brings along additional requirements which should be considered before algorithm design process.

- Wearable technology:

  Especially in military usage, hardware to be mounted should be light-weight, easy to be wear and should not allowed to be mounted in a wrong way by the user. Considering shoe-mounted inertial navigation some researches like [4] shows that best navigation performance can be achieved when the sensor is mounted on forefoot. There is also another conceptual design such as the inertial sensor is located inside the shoe insole [5].

- Low cost:

  Performance of INS highly effected from quality of the sensor and especially sensors with higher grades can make harder to achieve a system design that fulfil the user requirements in a cost-effective manner.

- Environmental Factors:

  From environmental conditions point of view, developed hardware bundle might be required to be comply with some level of sealing effectiveness against intrusion (IP level), as well as they might be required to function under extreme temperatures. This might affect the calibration quality of the sensor for especially temperature change in order to prevent additional noise/drift contribution to the system. Another important environmental disturbance is magnetic field interference which also has considerable impact on heading angle estimation.

- Data Loss:

  To use the system ergonomically, some approaches prefer to transmit inertial signal data using wireless communication which may cause data loss during communication. Considering high-dynamic change for both angular velocity and acceleration measurements during swing phase of walking/running motion, data loss over an acceptable limit may result as high error on integration process. As shown in Figure 2-1 navigation estimation outputs (blue line) follows the ground truth (red dots) at beginning, however sudden positioning error caused by consecutive data loss (as shown in red circle) that carries over to the end of the navigation scenario.

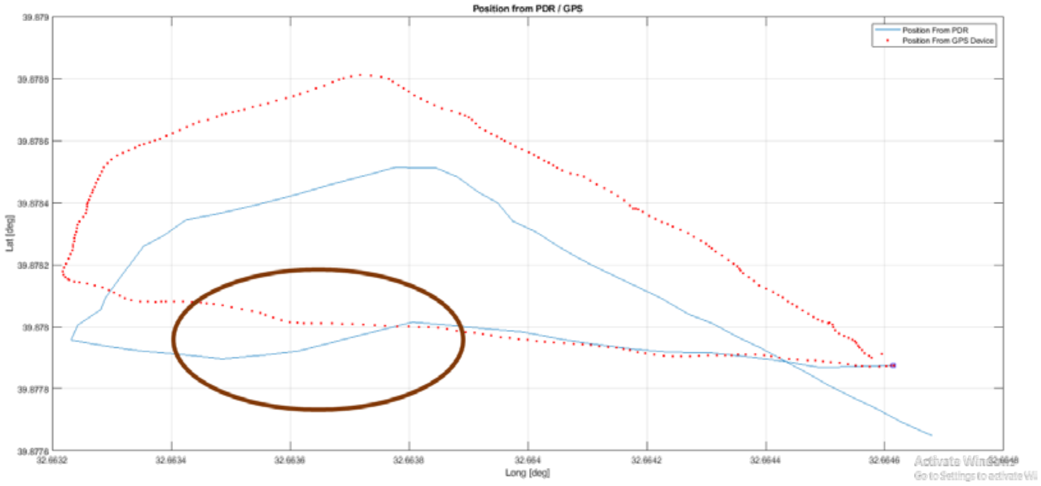

Figure 2-1: Positioning error caused by consecutive data loss.

- Indoor / Outdoor Usage:

  Requirements may differ regarding to different use case scenarios such as indoor / outdoor usage. For instance, there might be more accurate altitude estimation required for indoor environment or generally we can mention about higher magnetic field disturbance for again indoor structures. On the other hand, despite of more GPS outages, there might be more external source opportunities can be included in fusion framework compared to outdoor usage.

- Different Motion Types:

  Most use cases for pedestrian navigation consist of walking motion. However, for other use cases, developed system should also function in an acceptable level for other motion types as well. This brings additional difficulties on algorithm design such as higher dynamic motions during running.

- Major Prior Calibration:

  There should not be a prior calibration that requires some infrastructure or requires complex training process for the user before usage of the system. For instance, in [6] quite accurate performance is achieved (5.5m error for 3.5 km) however, mentioned L-shaped calibration loop has to be walked first in order to capture IMU’s directional drift and gain errors for trajectory estimation which might be not applicable for a real-world scenario. And there is no further information regarding to system performance without this prior calibration process.

- Subject Invariant Consistent Performance:

  Developed system should be insensitive to user variance, as well as achieving acceptable accuracy for different motion types and speed. While strap-down Inertial Navigation System (INS) equations do not affect from these matters, traditional threshold based ZVD techniques could not detect stance phase for all motion types with fixed thresholds and it is not possible to find a global threshold value for all kind of motions and subjects. Our experience shows, when the foot movement is slow, e.g. when walking at comfortable speed, conventional ZUPT detectors work well. But when the human dynamics increase, e.g. running, the performance of existing detectors tends to decrease, resulting in false or missed detected ZUPT.

3.0 ZVD DESIGN APPROACH

Regardless of the developed algorithm or the quality of the sensor used, the ZUPT performance has a significant impact on navigation errors. In addition, especially for running movement, since the gait vary from person to person and according to running speed, it becomes very difficult to detect stance region with traditional threshold-based methods. In Figure 3-1, since the speed and step pattern of the person changed during the run on a 400-meter-long circular track with 12 kph of running pace, deterioration occurred in the navigation outputs, despite the best threshold value selected. From the same figure it can be seen that deterioration will be higher when the running speed increased to 20 kph from 12 kph.

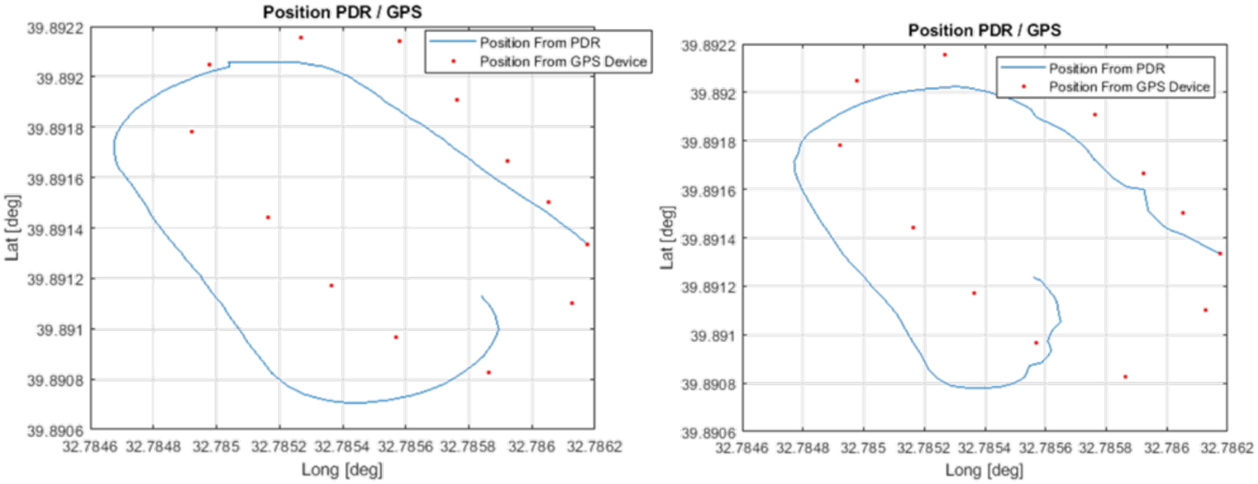

Figure 3-1: Position estimation with conventional methods @ 12 kph (left) and @ 20 kph running.

For this reason, a robust ZUPT design is required for both running and walking, which does not require an adjustment according to the person or speed, in other words, not based on threshold. In many studies, the consensus is that taking measurements from the stationary phase during stepping and triggering the verification phase in the Kalman Filter increases the navigation performance. However, according to our inferences, it is better to choose the closest points to the stationary region instead of taking as many measurements as possible. This is because the time between two successive steps, in other words, the INS model states calculated without the aid of any ZUPT do not deviate much enough. Therefore, in order to correct these low deviations, it is more logical to select the closest points to the stationary region and include them in the compensation process instead of taking measurements from as many stationary regions as possible. With this approach, the closest points to the stationary region were determined on the GLRT statistical signal presented in [7] where a statistical binary hypothesis test, based on combined information from gyro and accelerometer data, for determining whether or not the foot is at a standstill and included in the validation phase of the Kalman Filter. Figure 3-2 shows the difference between the threshold-based ZUPT method and the newly developed method.

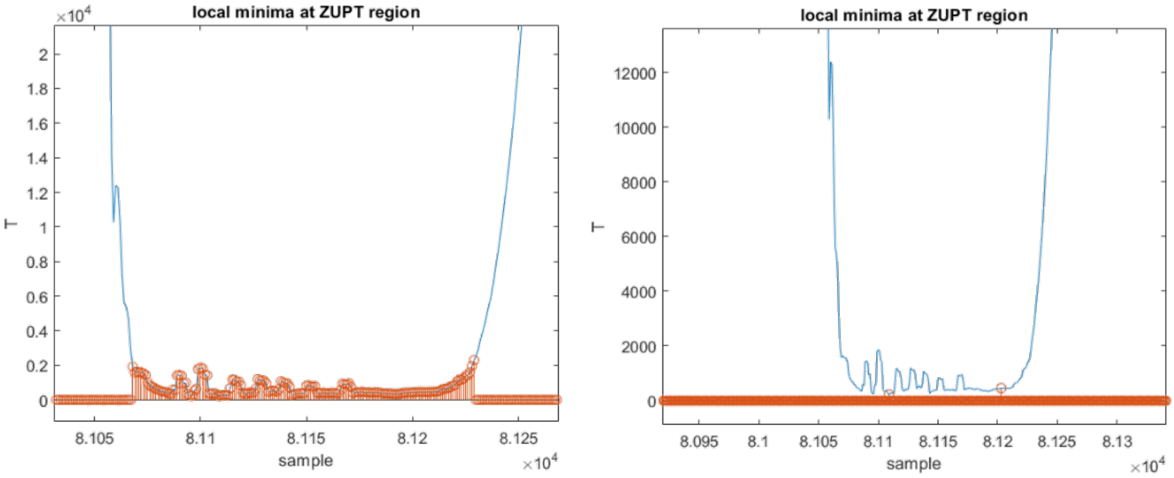

Figure 3-2: Stance phase detection: conventional threshold based (left) vs suggested (right).

The new navigation output obtained by applying the newly developed ZUPT detection algorithm to the scenario shown in Figure 3-3. The error in the 400m-long closed-loop trajectory is decreased to 15m from 37m and to 29m from 54m for 12kph and 20 kph running speeds respectively.

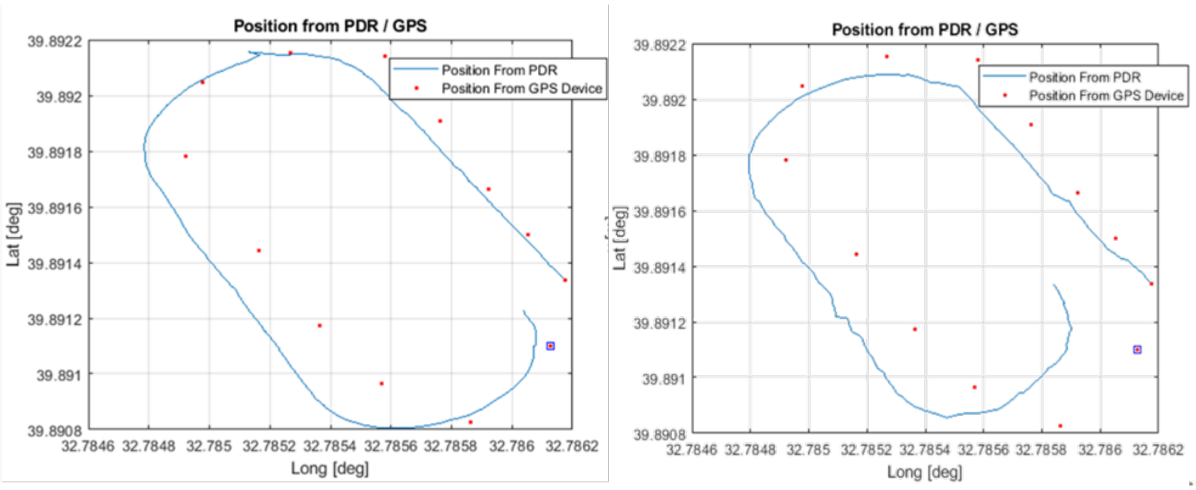

Figure 3-3: Position estimation with new method @ 12 kph (left) and @ 20 kph running.

The improvement in navigation performance can be easily noticed from the Figure. Despite the different speed segments during the run, the new ZUPT algorithm was able to find points closest to zero speed and feed more accurate measurements to the EKF framework. As can be easily seen from the figure, the main reason for the deviation in position is the error in the heading angle. This error is actually due to non-zero velocity movement in the zero-velocity assumption region and higher g-sensitivity for gyro measurements, which are classified under systematic errors. This non-zero velocity concept is referred to as "residual velocity" in the literature, and there are studies as in [2] to estimate these velocities. However, this issue was not included in the analyses made within the scope of this study. As can be seen in Figure 3-4, when residual velocity estimations provide to the framework as soft measurements, navigation performance is improved further due decreased heading angle error.

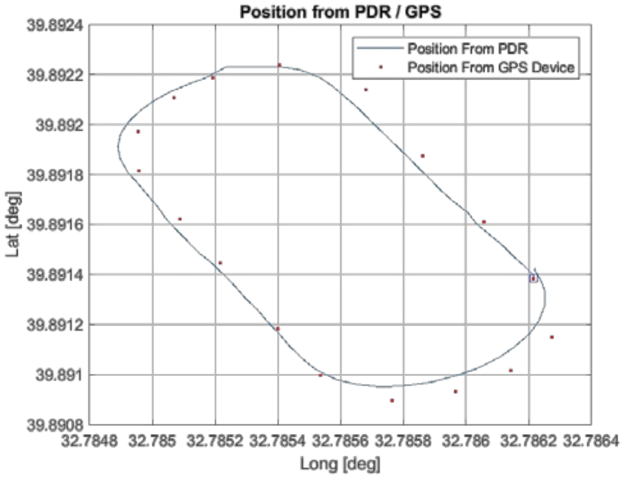

Figure 3-4: Position estimation with new method and residual velocity measurement @ 12 kph.

It may not possible to verify the innovation developed by reviewing the improvement over only one scenario. In the next section, the validation approach developed to ensure that the system works robustly and produces consistent results will be discussed.

4.0 VALIDATION

In this section, it is aimed to reveal the position estimation performance of the developed new ZUPT aided PDR (Pedestrian Dead Reckoning) system when the person is walking and running. Since the purpose of the validation studies is to examine the consistent operation of the newly developed ZUPT aided navigation system and due to the fact that the dynamics in walking movement and the variability from person to person are less than running movement, different approaches will be followed for walking and running movements.

For each walking/running scenario, the estimation error is calculated as a percentage by taking the ratio of the difference (in meters) between the Ground Truth GPS point at the end point and the GPS point predicted by the PDR to the total walking distance (in meters).

4.1 Validation for Walking Motion

As mentioned before, the aim of this study is to create a structure that can work consistently with different users and to take actions that will increase the navigation performance in the next stages. In this context, two different approaches were followed in the validation of the study, in which the newly developed algorithm was applied to gait scenarios.

The first approach is that there are different magnetic field interaction profiles in different locations, but the diversity of individuals is low; The second approach also defines the approach in which the same path is walked by different subjects.

4.1.1 Magnetic Field Disturbance Dependency

Data were collected from the three different environments as urban, semi-urban and rural areas, which differs according to magnetic field interference in the evaluation of position estimation performance for the person's walking motion. We are not going to investigate continuous disturbance as in Indoor Environment but review instantaneous disturbances may occur in various scenarios for various environments.

4.1.1.1 Rural Area Definition

Within the scope of this study, the regions defined as Rural/Terrestrial Areas were evaluated where instantaneous magnetic field interferences are very rare and low (Approximate Nominal Value ± 5uT). There may be instantaneous deviations exceeding the deviation of ± 5uT, and there is no objective assessment of this situation. Values are determined empirically and based on experience. The sample magnetic field norm graph for the walking scenario in the rural area is as in Figure 4-1.

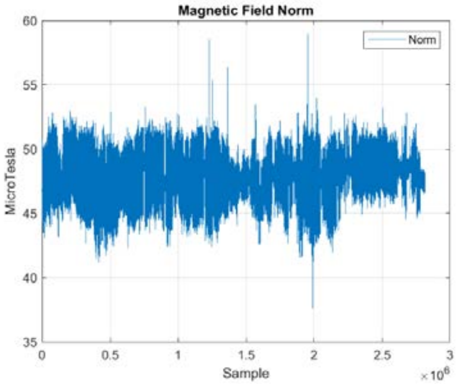

Figure 4-1: An example of magnetic field measurement for rural area.

Position estimation studies performed in 10km long terrestrial environment and in the Figure 4-2 result is presented. Results show that proposed PDR algorithm achieves about 157m which corresponds to %1.57 positioning error at the end of the track. This study also reveals that the system is suitable for long range and/or duration operations thanks to its low energy requirement.

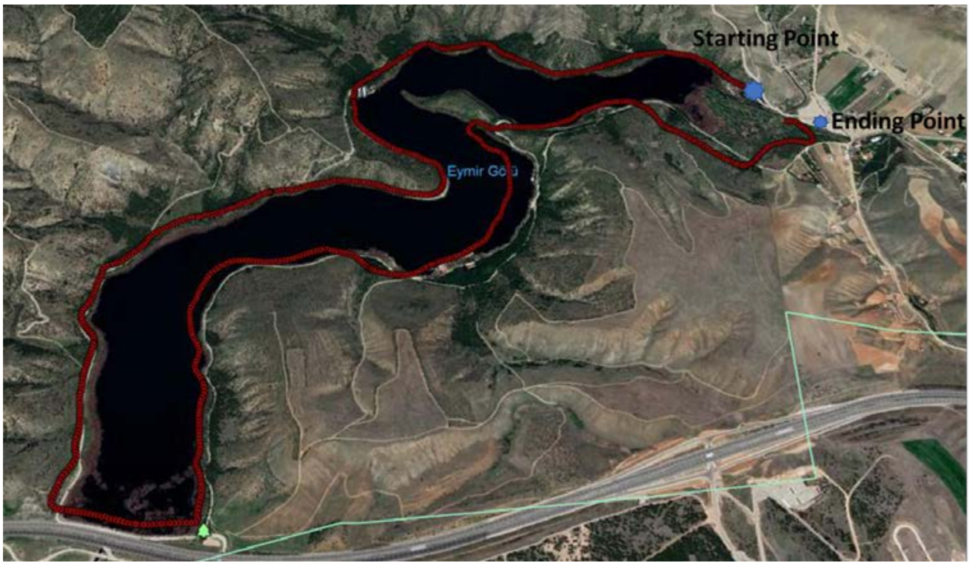

Figure 4-2: Position estimation for walking in terrestrial environment.

4.1.1.2 Semi-Urban Area Definition

Within the scope of this study, the regions defined as Semi-Urban Areas were evaluated as non-crowded or closer settlements to the city where instantaneous magnetic field disturbances are relatively higher and frequent (Approximately Nominal Value ± 20uT) than in the Rural Area. There may be instantaneous deviations exceeding the deviation of ± 20uT, and there is no objective assessment of this situation. Values are determined empirically and based on experience. Sample magnetic field norm graph for Semi-urban walking scenario is as in Figure 4-3.

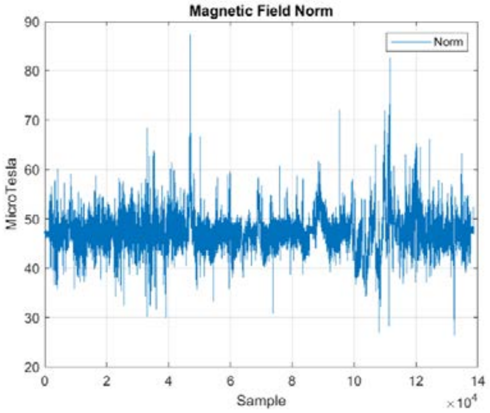

Figure 4-3: An example of magnetic field measurement for semi-urban area.

As an example, for a 1.7 km-long walking scenario in an urban environment, 34m error, also corresponds to %2 error, is occurred at the ending point of the closed-loop trajectory and the position estimation is shown in Figure 4-4. (Yellow line is ground truth; blue dots are position estimations)

Figure 4-4: Position estimation for walking in semi-urban environment.

4.1.1.3 Urban Area Definition

Within the scope of this study, areas defined as Urban Areas where instantaneous magnetic field disturbances are high (> Nominal value + 20uT, < Nominal value - 20uT), crowded urban environments, structures with high metallic materials but not indoor environments. Again, values are determined empirically and based on experience. The sample magnetic field norm graph for the urban area walking scenario is as in Figure 4-5.

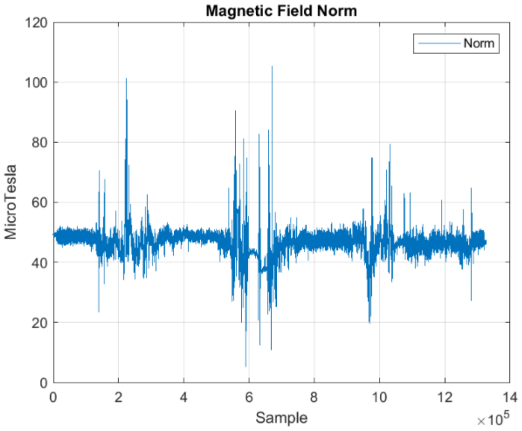

Figure 4-5: An example of magnetic field measurement for urban area.

As an example, for a 2.38 km-long walking scenario in an urban environment, 135m error, also corresponds to %5.78 error, is occurred at the ending point of the open-loop trajectory and the position estimation is shown in Figure 4-6. (Blacked dots are GPS records; red dots are position estimations)

Figure 4-6: Position estimation for walking in urban environment.

4.1.1.4 Overall Results for Walking Scenarios

In order to bring together the different environment scenarios described in the previous 3 sections, a data set of approximately 90 km was created by collecting 45 walking data from 3 people from 26 different locations. The distribution of 45 scenarios collected according to the environments is given in Table 4-1.

Table 4-1: Positioning error rates regarding to environmental difference for walking

Environment	Total Distance Covered [m]	Mean Error [%]	Standard Deviation [%]
Rural	24550	1.42	0.3663
Semi-Urban	45028	1.6157	0.7539
Urban	24667	3.5547	1.6124
All Data	94245	2.1497	1.3681

Figure 4-7 shows the occurrence frequency of navigation error calculated as a percentage according to the previously defined navigation performance criteria. The purple dots on the graph are urban areas; yellow dots semi-urban; the red dots show the rural area results. As expected, error rates were higher in residential scenarios than in other environments, especially since magnetic field measurements were used to calculate the heading angle. The frequency of occurrence will vary according to the distribution of the environments used while creating the dataset. In the approach taken in this study, considering that such a system would be needed more in residential / semi-inhabited areas, more data was collected from these environments. Based on this dataset, the average error rate was calculated as 2.15% and the standard deviation value in the error rate was calculated as 1.37%.

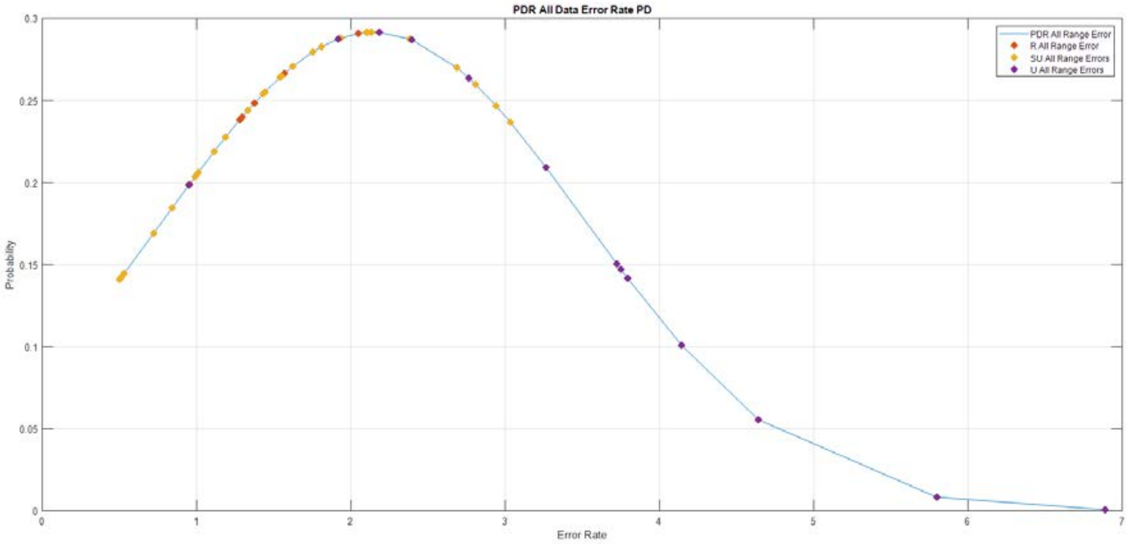

Figure 4-7: Positioning error distribution for walking motion.

4.1.2 Subject Invariance Consistency for Walking Scenario

In order to test the dependence of navigation performance on person differences in gait scenarios, gait data were collected from 6 people in a 7 km area where there is no effective magnetic field interaction shown in Figure 4-8.

As can be seen from Table 4-2, the error rate varies between 1.1% and 2% for different individuals. Since it is compatible with the error metrics calculated for the rural area in Table 4-1, it can be concluded that the developed algorithm gives consistent results for person differences for walking motion.

Figure 4-8: Trajectory for validation of subject invariant performance for walking motion.

Table 4-2: Positioning error rates for 6 subjects

Subject	Distance Covered [m]	Error [m]	Error [%]
Subject - 1	6995	78	1.115082
Subject - 2	6995	121	1.729807
Subject - 3	6995	80	1.143674
Subject - 4	6995	142	2.030021
Subject - 5	6995	122	1.744103
Subject - 6	6995	117	1.672623

4.2 Validation for Running Motion

In order to test the consistent operation of the algorithm, which was developed depending on both the running speed and the running style of the person (the way the foot hits the ground, etc.) in the running movement, data were collected from 3 different groups of 15 people with different height and weight characteristics in 3 different locations. Since the consistent operation of the newly developed ZUPT method will be analysed here, environments without effective magnetic interaction are preferred in order to reduce external factors that may affect the position error. It should be noted that incorrectly detecting or not detecting the ZUPT zone, especially for the running scenario, will produce much more navigation errors than walking motion. Therefore, the consistent operation of ZUPT for the running scenario is very critical in terms of navigation performance.

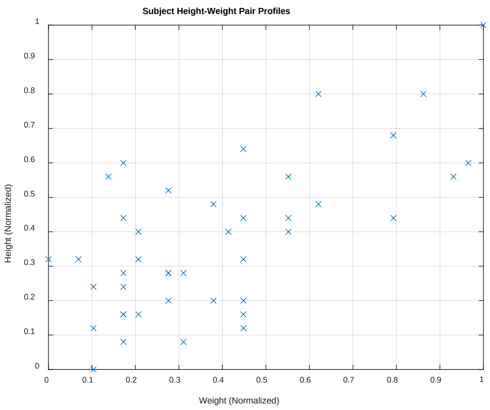

Figure 4-9: Subject height/weight distribution for running tests.

In this context, it was deemed appropriate to collect data from 45 individuals whose height/weight distributions were normalized in Figure 4-9 in order to ensure the necessary individual diversity. According to the distribution presented in Figure 4-9, although there are no individuals in the group that fit the definition of "tall and thin" and "short and overweight", it can be assumed that there is a logical distribution for use in the field. In addition, since the running style profile could not be fitted to any metric, it was thought that testing on 45 subjects might cover this variation.

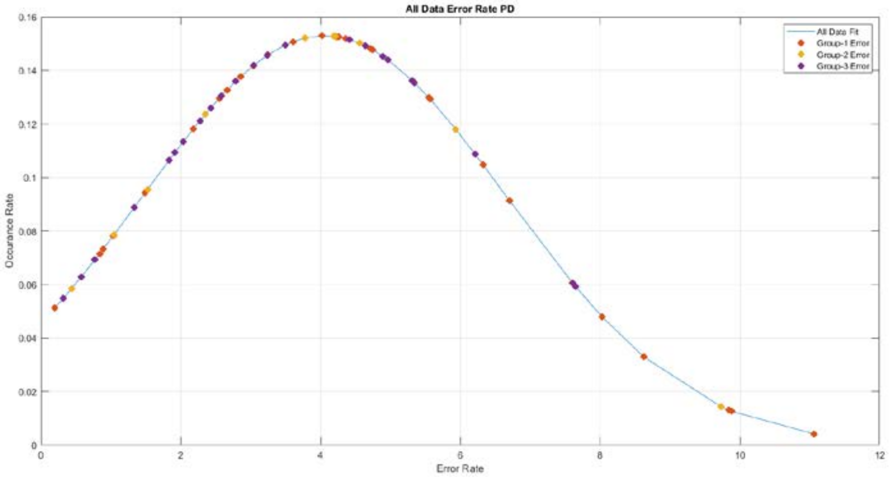

Figure 4-10: Positioning error distribution for running motion.

Table 4-3: Positioning error rates for running motion validation tests.

	Total Distance [m]	Mean Error [%]	Standard Deviation [%]
Group – 1	34000	4.5213	2.963
Group – 2	23150	4.133503	2.626025
Group – 3	25800	3.464417	2.097108
Total	82950	4.055449	2.608127

According to the error rate distribution in Figure 4-10, the error rate generally shows a majority between 2% and 5%. Based on this dataset, the average error rate was calculated as 2.15% and the standard deviation value in the error rate was calculated as 1.36%. In Table 4-3, the total distance covered, mean error rate and standard deviation values in error rate are given separately and combined for the groups. Considering these values, it can be concluded that consistent results were obtained in different groups and in the aggregate.

5.0 CONCLUSIONS

In this study, the design of a shoe-mounted IMU-based inertial navigation system that covers both walking and running movements in different people in a way that will give consistent results is explained. The aim here is to first reach a consistent structure and study the issues to improve the system navigation performance in the next steps. The consistency of the results will be examined, rather than how good or bad the performance metrics are. The conclusion that the developed new ZUPT method gives consistent results for different people for running and walking movements can be reached from the non-high standard deviation values in error rates. New suggested ZUPT method ensures that high non-zero velocities are prevented to be included in the EKF correction phase, but closest points to stationary phase are aimed to be detected. The results obtained are promising, showing that long-term navigation is possible without considerable divergence and with low errors rates in walking and running scenarios. In addition to the promising results obtained in the case system functions standalone, authors highly believe that, developed system can be integrated as the core component into the cooperative localization framework.

As mentioned, magnetic field measurements were used to calculate the heading angle. Environmental magnetic field interactions for walking motion were seen as the main factor reducing navigation performance and are reflected in Table 4-1. Surely this also applies to the running movement, although this is not reviewed in this paper. For this reason, studies should be carried out to include gyroscope measurements, which will not be affected by magnetic field interactions, into the process. The situation is slightly different for the running movement. In this case, the heading angle deviation is due to the fact that the actual velocity is different from zero in the zero-velocity approximation during stance phase. For this reason, methods in which gyroscope measurements are included in the process, this time includes more dynamic state (such as high g-accelerations), should be investigated.

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