# Implementing a Pedestrian Tracker Using Low-Cost Bluetooth Inertial Sensors

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**Abstract.** Foot-mounted inertial measurement units (IMUs) are becoming the basis for many pedestrian positioning systems as a component of accurate indoor navigation. However, most of solutions that implement low-cost IMUs are often connected to a laptop by a wired connection which interferes with the pedestrian movements. Moreover, nobody walks carrying a laptop but a smartphone. Smartphones are attractive platforms for researchers to collect data coming from several sensors due to their small size, low-cost, and the fact that they are already carried routinely by most people. Therefore, this paper (i) describes a custom-built foot-mounted pedestrian indoor localization system based on commercially available low-cost inertial sensors connected wirelessly (via Bluetooth) to a smartphone, and (ii) demonstrates the capability of smartphones to be used as the target of a wirelessly IMU-based positioning system where raw IMU data will be processed in real time. We have tested the pedestrian tracker with commercial devices in a five floor building with reasonable results (accumulated error lower than 1%).

## 1 Introduction

The use of location data to control normal day features are being more popular in recent years not only for security applications, but also for mass market applications. Applications of location data include Location-Based Services (LBS) such as pedestrian navigation in complex indoor buildings, inclusion of elders or disabled citizens in Ambient Assisted Living (AAL) scenarios, support to first-aid responders such as firemen or policemen in risky situations, the proactive supply of information at specific locations for museum visitors, or the customized advertising in shopping malls, among others [1]. Outdoors, most of the positioning applications rely on global navigation satellite systems (GNSS). However, satellite signals get severely degraded in indoor environments such as inside buildings, urban canyons or tunnels. For these indoor environments, many local positioning systems (LPS) have been developed during the past two decades based on different technologies, and utilizing many physical signals (see [2] for a LPS survey). After all this research effort, it is becoming a fact that none of these technologies clearly outperforms the others. Thus, a current trend in addressing indoor localization is to fuse already deployed technologies.

An increasing popular indoor positioning solution combines pedestrian dead-reckoning (PDR), using foot-mounted inertial measurement units (IMUs), with already

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deployed beacon-based technologies to provide indoor and accurate long-time navigation [3, 4, 5]. Indeed, PDR is the basis for many indoor localization techniques (see [6] for a tutorial on PDR). Despite the increasing popularity of methods which use PDR techniques based on foot-mounted IMUs, most of them connect the IMU to a laptop by a wired connection (usually by USB) which interferes with the human movements. The existing commercial IMUs with wireless connectivity would solve that problem, but they are relatively high cost (e.g. MTw from Xsens Technologies). Other solutions lose the sense of mobility because of the sensors signals are proceessed on a laptop. Nevertheless, nobody walks with a laptop but with a tablet or smartphone.

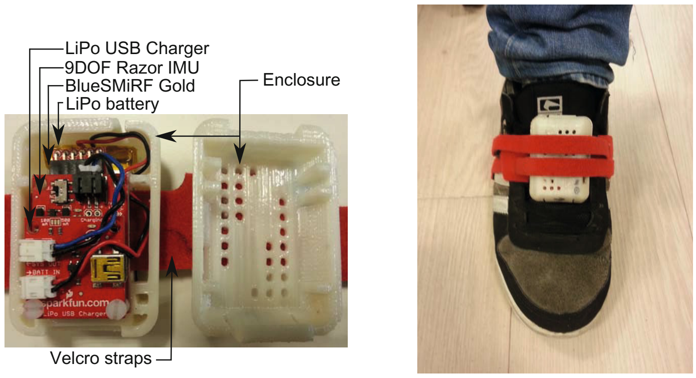
Therefore, the contribution of this work is twofold: (i) making the connectivity to the IMU wireless and of lower-cost by developing a custom-built foot-mounted pedestrian indoor localization system based on commercially available low-cost inertial sensors connected via Bluetooth to a smartphone (or tablet), and (ii) processing the IMU signals in the smartphone (or tablet) at real time by developing a LPS framework on Android operating platform. Thus, you can easily, and at low cost, implement our Bluetooth foot-mounted IMU and apply the already developed techniques with minimum custom configuration.

The paper is structured as follows: Section 2 describes the low-cost IMU with Bluetooth connectivity implemented in this work. Section 3 gives a brief overview on inertial pedestrian dead-reckoning and describes the PDR method to be developed on Android and which performance will be evaluated. Section 4 shows our experimental setup and empirical positioning results. Section 5 gives some final conclusions.

## 2 Low-Cost Bluetooth Inertial Sensors

The low-cost IMU conected via Bluetooth to a smartphone discussed in this paper consists of three modules - an IMU with three sensors, a Bluetooth modem, and a lithium polymer (LiPo) battery - to wirelessly give the smartphone the data gathered by the IMU. In this work we have used the modules provided by SparkFun Electronics. As IMU we used the *9DOF Razor IMU* which consists of a MEMS triple-axis accelerometer (ADXL345), a triple-axis gyro (ITG-3200), and a triple-axis magnetometer (HMC5883L) to give us nine degrees of inertial measurements [7, 8, 9]. As Bluetooth modem we used the *BlueSMiRF Gold* which works wirelessly as a serial (RX/TX) pipe. Both IMU and Bluetooth modem are powered by the very slim and extremely light weight *850 mAh LiPo battery*.

To set up the hardware, we follow the online tutorial describing how to build an attitude and heading reference system (AHRS) using the SparkFun *9DOF Razor IMU* [10]. Basically, connecting the *9DOF Razor IMU* to the *BlueSMiRF Gold* modem attending their I/O header layouts. The *LiPo battery* powers the *9DOF Razor IMU* thorough an USB charger also used to charge the battery. After assembling the three modules we designed an enclosure with a 3D printer in order to mount them easier on the foot. Figure 1(a) shows the whole system. The modules are mounted one on the top of the other minimizing the space that they take up. The velcro straps are used to fix the IMU to the foot as it is shown in Figure 1(b). Therefore, with no more than 175$ (taken current SparkFun Electronics prices) you can implement a low-cost Bluetooth foot-mounted IMU for pedestrian tracking.




(a) Low-cost Bluetooth IMU (b) Foot-mounted IMU

**Fig. 1.** Pedestrian tracker. (a) Low-cost Bluetooth IMU into the enclosure, and (b) attached to the right foot.

The parametrization of the IMU is application dependent. As a result, no universal parameters can be given. However, some groups of parameters can still be identified [11]. The parameters of the hardware set-up are only the sensor placement/mounting and the sampling frequency. On the one hand, a rule of thumb is that for inertial navigation systems (INS) employing low-cost sensors, the position error is proportional to the cube of the operational time which means that free-inertial navigation is only feasible for a few seconds [12]. Therefore, we place the IMU on the foot for using the well-known zero velocity update (ZUPT) method and thus bounding the error growth. On the other hand, after an experimental analysis of human motion sampling, E. Munoz et al. noted that the limiting signals in terms of bandwidth are those from the accelerometer due to the high frequencies generated when the foot hits the floor [13]. They established that the sampling frequency should lie between 200 Hz - when using flat shoes - and 300 Hz - when high heels. In this work we used flat shoes therefore, we set the accelerometer data rate to 200 Hz. For the gyro the bandwidth needed is not greater than 50 Hz, therefore the sampling frequency would be 100 Hz [13].

The external parameters are the trajectory and the sensors output. Regarding the sensors output W.T. Faulkner et al. found that altitude errors in pedestrian-tracking systems are due to the accelerations of the foot exceeding the dynamic range of the accelerometer [14]. They noted that accelerations can reach $\pm 10g$ when walking, and $\pm 13g$ when running. Therefore, for the best results the accelerometer is configured in a 13-bit resolution ($4mg/LSB$) to reach a range up to $\pm 13g$. Likewise, the gyro is configured with a full-scale range of $\pm 2000/s$ corresponding to a sensitivity of $0.0695/s$ per $LSB$. Due to we focus on indoor environments in this work, the magnetometer sensor is not used due to the indoor magnetic disturbances. Thus, the raw data to be sent wirelessly consists of 12 bytes, 6 for the accelerometer (2 by axis) at 200 Hz data rate, and 6 for the gyro (2 by axis) at 100 Hz data rate. The raw outputs of sensors are collected by the *9DOF Razor IMU* on-board *ATmega328* microcontroller and output over the serial interface to the Bluetooth modem.

## 3 Inertial Pedestrian Dead-Reckoning

Dead reckoning is the process of estimating an object's position by tracking its movements relative to a known starting point and attitude. There are two alternative PDR integration methods: those that estimate position by integrating step lengths (SL) and orientation estimations at each detected step [15, 16]. And, those with a foot-mounted IMU, implementing an INS on a Kalman filter [17, 18, 19, 6]. Both SL and INS-KF share the same main drawback, the drift, the accumulation of positioning errors during the dead-reckoning integration. Without resetting the drift, the velocity (position estimation) error would increase linearly (quadratically) with time. However, we can remove the velocity error applying the well-known ZUPT method which detects the *stance phase* - that is, when the IMU is stationary - and thus we can reset the estimated velocity to zero and adjust the estimated position [17]. Detecting when an IMU is stationary can be challenging, this has made foot-mounted IMU's our choice for PDR. Furthermore, INS-KF method performs better than SL since velocity and position errors are correlated, and the cross-covariances let the KF correct the position (and not only the velocity) during a ZUPT.

The article published in 2005 by E. Foxlin is probably the most cited work in this area [17]. He explains how to take advantage of correlated position/velocity errors in KF to also remove most position errors with each ZUPT. A. Jimenez et al. gives a more complete description of the implementation process, and a more recently work by C. Fischer et al. outlines a tutorial for implementing a reasonably accurate tracker using a foot-mounted IMU with minimum custom configuration [19] and [6], respectively. In this paper, we take the raw data collected by the smartphone through its Bluetooth interface and transform them into successive positions and orientations. For this transformation we implement an INS-KF method taking the standard inertial PDR method described in [6] with some variations explained below:

- *System initialization*: While the user's foot remains motionless on the floor (previous to start walking), the acceleration and rate-of-turn signals are recorded. On the one hand, the acceleration data is used to estimate the roll and pitch angles (the yaw is provided by the user) which give us the initial rotation matrix. This initial matrix is refined *a posteriori* with successive acceleration measurements on an extended Kalman filter while the foot remains motionless. On the other hand, the mean of gyro data is computed as the bias to be subtracted from successive gyro measurements.
- *Detect a stationary phase*: Instead of only using a simple threshold on the magnitude of the gyro rate-of-turn measurements, we implement a triple-condition algorithm which not only takes into account the magnitude of the gyro measurements but also the magnitude of the acceleration and its local variance [19].
- *Detect if going up/down*: Similarly to ZUPT method, we can remove the position error in altitude on the Kalman filter while the IMU remains at the same floor. Detecting if the IMU is going up/down can be accomplished by a two-condition algorithm which takes into account the local variance of the estimated position in altitude and its magnitude change within the last period of time (e.g. one second).
- *Heading drift reduction*: Heading drift still remains despite using ZUPT since the heading error is unobservable. However, the majority of buildings have dominant

directions defined by the orientation of their corridors and, a person walks most of the time along straight-line paths parallel to these dominant directions. Therefore, assuming the person walks in indoor buildings we can implement the so-called heuristic drif elimination (HDE) proposed by Borenstein and Ojeda or a more recently work by A. Jimenez et al. improving the previous one (iHDE) [20] and [21], respectively.

## 4 Evaluation

The pedestrian tracker using low-cost Bluetooth inertial sensors has been developed on Android, a mobile operating platform which nowadays controls most of the smartphones. As a way to verify its behaviour under a real environment it has been tested using a commercial smartphone which processes the raw IMU data in real time.

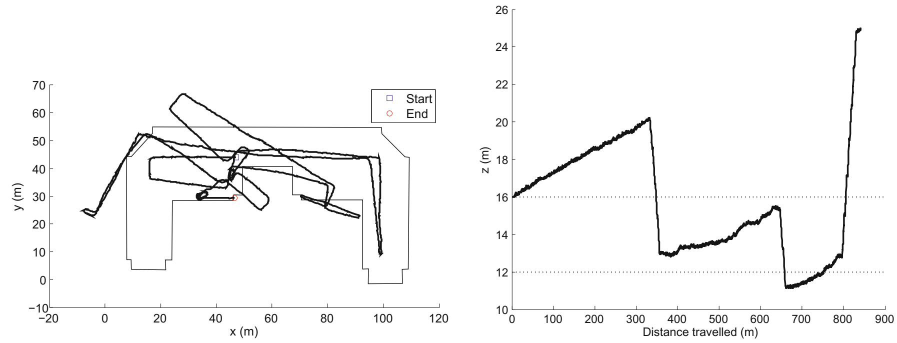
### 4.1 Experimental Setup

For the experimental evaluation we conducted real trials at the building of the Faculty of Engineering (Deusto University) in the city of Bilbao, whose floor map is shown in Figure 2. This five floor building is approximately 112 m long and 62 m wide. The approximately 800 m long path followed goes by three floors, starting in the 5*th* floor (at 16 m height), going down to the 3*rd* floor (at 8 m height) by the stairs, once more going down to the 2*nd* floor (at 4 m height), and finally returning to the starting point going up to the 5*th* floor. In the experiments the target is a person who walks more or less at constant speed, and carries the foot-mounted IMU detailed in section 2 and the Galaxy Nexus GT-i9250 smartphone. This smartphone incorporates the Broadcom BCM4330 single chip device providing with Bluetooth *4.0+HS* connectivity among others handheld wireless systems, and a 1.5 GHz dual core ARM-based processor which implements the pedestrian tracker algorithm in real time.

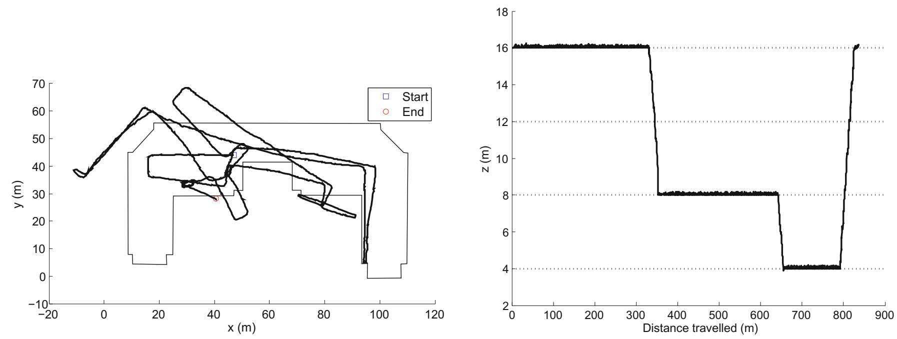
### 4.2 Results

We do not aim to give a precise comparison of different PDR heuristics with their optimal parameters. Rather, we want to evaluate the performance of a custom-built foot-mounted pedestrian tracker based on commercially available low-cost inertial sensors connected via Bluetooth to a smartphone which processed the raw IMU data in real time. All position estimates are relative to the initial position and heading, therefore a small error early in the path would have a significant effect later on.

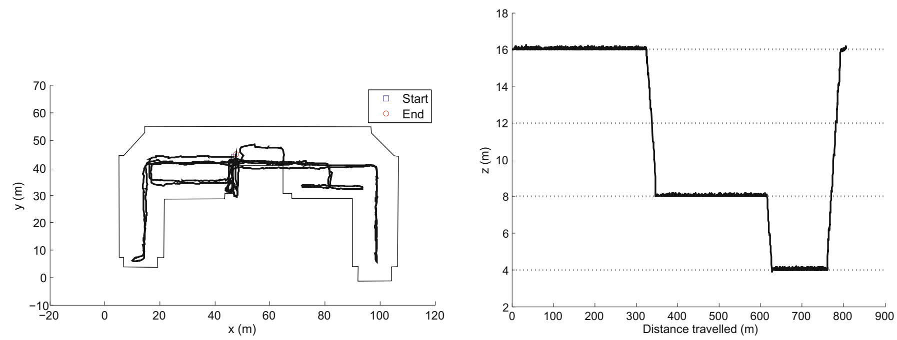
Figure 2 shows the horizontal and altitude plots from our three implementations: ZUPT heuristic, ZUPT and going up/down heuristics, and ZUPT, going up/down and iHDE heuristics. All of them share the same framework, the standard inertial PDR method described in [6], using the initial transformation matrix provided by the gathered initial accelerometers data, and removing the gyro bias computed at the beginning of the trial. Acceleration and gyro data rate at 200 Hz and 100 Hz, respectively, gave the best results. Lower data rates degraded the performance, but higher rates did not bring




(a) KF ZUPT




(c) KF ZUPT and going up/down




(e) KF ZUPT, going up/down and iHDE

**Fig. 2.** Plots for a 800 m long walk through the Faculty of Engineering at the University of Deusto. Each pair of plots shows the horizontal position (left) and altitude (right) for (a) KF with ZUPT heuristic, (b) KF with ZUPT and going up/down heuristics, and (c) KF with ZUPT, going up/down and iHDE heuristics.

any noticeable improvement. The KF implementation with heading drift and altitude error elimination always provide the best results. As a way to compute the accuracy of the pedestrian tracker, the route started and finished at the same point. Therefore, the accumulated positioning error is computed as the 3D Euclidean distance between the starting and finishing positions with respect to the total traveled distance. Thus, applying iHDE and going up/down heuristics, the total accumulated error is 2 m, i.e. 0.25% of the total traveled distance. The results were reasonable (accumulated error lower than 1%) but would improve by testing different environments with different users, which probably need better tuning the KF and the parameters of the implemented heuristics.

## 5 Conclusions

The discussion in this paper has given an overview of the possibilities of smartphones to be used as the target of a wirelessly IMU-based positioning system. Firstly, we have described a custom-built foot-mounted IMU based on commercially available low-cost inertial sensors to be connected wirelessly to a smartphone. Secondly, we have demonstrated the capability of smartphones to process raw IMU data in real time which are received wirelessly up to 200 Hz data rate. Finally, we have tested the pedestrian tracker with commercial devices in a five floor building achieving an accumulated error lower than 1%. As future work we are going to fuse the raw IMU data with the smartphone sensors data such as WiFi and GPS trying to provide accurate and long-time navigation.

## References


[1] Harle, R.: A survey of indoor inertial positioning systems for pedestrians. IEEE Communications Surveys and Tutorials 15, 1281–1293 (2013)

[2] Gu, Y., Lo, A., Niemegeers, I.: A survey of indoor positioning systems for wireless personal networks. IEEE Communications Surveys & Tutorials 11, 13–32 (2009)

[3] Zampella, F., Bahillo, A., Prieto, J., Jimenez, A.R., Seco, F.: Pedestrian navigation fusing inertial and rss/tof measurements with adaptive movement/measurement models: Experimental evaluation and theoretical limits. Sensors and Actuators A: Physical 203, 249–260 (2013)

[4] Zhang, K., Zhu, M., Retscher, G., Wu, F., Cartwright, W.: Three-dimension indoor positioning algorithms using an integrated rfid/ins system in multi-storey buildings. In: Gartner, G., Rehrl, K. (eds.) Location Based Services and TeleCartography II - From Sensor Fusion to Context Models. Lecture Notes in Geoinformation and Cartography, pp. 373–386. Springer, Heidelberg (2008)

[5] Ruiz, A.R.J., Granja, F.S., Honorato, J.C.P., Rosas, J.I.G.: Accurate pedestrian indoor navigation by tightly coupling foot-mounted imu and rfid measurements. IEEE T. Instrumentation and Measurement 61, 178–189 (2012)

[6] Fischer, C., Sukumar, P.T., Hazas, M.: Tutorial: Implementing a pedestrian tracker using inertial sensors. IEEE Pervasive Computing 12, 17–27 (2013)

[7] Analog Devices: Digital Accelerometer. ADXL345 Datasheet, pp. 1–40 (2013)

[8] InvenSense Inc.: Digital Gyroscope. ITG-3200 Product Specification, pp. 1–40 (2010)

[9] Honeywell International Inc.: Digital Compass. HMC5883L Datasheet, pp. 1–20 (2010)

[10] GitHub: Tutorial: Building an AHRS using the SparkFun “9DOF Razor IMU” or “9DOF Sensor Stick”. HMC5883L Datasheet (accessed May 2014)

[11] Nilsson, J.O., Skog, I., Handel, P.: Performance characterisation of foot-mounted zupt-aided inss and other related systems. In: International Conference on Indoor Positioning and Indoor Navigation (IPIN), pp. 1–7. IEEE (2010)
[12] El-Sheimy, N., Niu, X.: The Promise of MEMS to the Navigation Community. Inside GNSS, 6+ (2007)
[13] Munoz, D., Heirich, O., Khinder, M., Robertson, P.: Optimal sampling frequency and bias error modeling for foot-mounted IMUs. In: International Conference on Indoor Positioning and Indoor Navigation (IPIN), pp. 1–9. IEEE (2013)
[14] Faulkner, W., Alwood, R., Taylor, D., Bohlin, J.: Altitude accuracy while tracking pedestrians using a boot-mounted IMU. In: Position Location and Navigation Symposium (PLANS), pp. 90–96. IEEE (2010)
[15] Ladetto, Q., Seeters, J., Sokolowski, S., Sagan, Z., Merminod, B.: Digital Magnetic Compass and Gyroscope for Dismounted Soldier Position and Navigation. Sensors and Electronics Technology Panel, NATO Research and Technology Agency Sensors, pp. 1–15 (2002)
[16] Stirling, R.: Development of a Pedestrian Navigation System Using Shoe Mounted Sensors. University of Alberta, Department of Mechanical Engineering (2004)
[17] Foxlin, E.: Pedestrian tracking with shoe-mounted inertial sensors. IEEE Comput. Graph. Appl. 25, 38–46 (2005)
[18] Feliz, R., Zalama, E., Garcia-Bermejo, G., Bohlin, J.: Pedestrian Tracking Using Inertial Sensors. Journal Physical Agents 3, 35–43 (2009)
[19] Jimenez, A.R., Granja, F.S., Prieto, J.C., Rosas, J.I.G.: Indoor pedestrian navigation using an ins/ekf framework for yaw drift reduction and a foot-mounted imu. In: Workshop on Positioning, Navigation and Communication, pp. 135–143. IEEE (2010)
[20] Borenstein, J., Ojeda, L.: Heuristic drift elimination for personnel tracking systems. Journal of Navigation 63, 591–606 (2010)
[21] Jimenez, A., Seco, F., Zampella, F., Prieto, J., Guevara, J.: Improved Heuristic Drift Elimination (iHDE) for pedestrian navigation in complex buildings. In: International Conference on Indoor Positioning and Indoor Navigation (IPIN), pp. 1–8. IEEE (2011)