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A Pedometer-Based System for Real-time Indoor Tracking on Mobile Devices

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***Abstract*— This paper describes the implementation and evaluation of a low-cost solution for real-time indoor tracking. It is based on a simple pedometer approach that uses data collected from sensors (accelerometers and compass) that are built-in on mobile devices to provide indoor tracking. A mobile application is used to display the indoor tracking outputs through an interactive user-interface (UI). Evaluation experiments of the system are carried out using Nokia mobile phones in a real indoor office scenario. Results are discussed showing the potential usability of our system. Further works will be focused on the accuracy improvement of our approach with the use of data filtering and interference reduction strategies.**

***Keywords*— Indoor tracking, mobile applications**

I. INTRODUCTION

Position tracking and localization of moving objects in indoor environments is a research field with various applications like finding and rescuing firefighters or other emergency first responders, location-aware computing, personal navigation assistance, mobile 3D audio, and mixed or augmented reality applications [1]. One of the main obstacles to the real-world deployment of location-sensitive wearable computing, including mixed reality (MR), is that current position-tracking technologies require an instrumented, marked, or RF premapped environment. Installing markers or instrumentation in advance is impractical for many mobile applications, and the hunt is on for a tracking method that will work reliably without preparation in any indoor or outdoor setting. Computer vision is the leading contender, but enormous challenges remain to develop a robust vision-based tracker for general-purpose use [2].

A practical solution to orientation-only tracking is to use inertial sensors such as microelectromechanical (MEMS) gyroscopes with drift correction performed by referencing the earth's gravity for pitch and roll, and the geomagnetic field for heading. The self-contained sensors work in indoor and outdoor environments.

Several works address indoor tracking for specific purposes [1]–[5], but always dealing with the intrinsic trade-off, accuracy versus infrastructural investments. In [1], a system for indoor 3D position tracking with an inertial measurement unit (IMU) and a marker-based video tracking with external cameras is presented. By combining inertial sensors and vision-based position data, the proposed system overcomes video measurement outages over short periods of time as well as IMU drift problems.

In [3] the authors present a hybrid indoor positioning solution combining angle-based localization, pedestrian dead reckoning and map filtering. The angle-based localization system provides absolute location estimates, whereas pedestrian dead reckoning (PDR) results in accurate shape and traversed route length without absolute location and heading information. PDR movements and angle-based location estimates are combined with a building vector map in a fusion filter, which is implemented through a particle filter. The approach was tested in different indoor environments with seamless positioning coverage and reasonable accuracy and infrastructural investments.

The experiment presented in [4] gets an excellent result, however it was performed with a full 6-degrees-of-freedom inertial measurement unit (IMU) attached to the user's boot and estimated the user's displacement with a technique known as "Zero Velocity Update"(ZUPT). The sensor location placement is not practical for user navigation application. In a previous work, the authors implemented the same system using a bulky, heavy and expensive IMU. Latter, they changed to a nano IMU which is cheaper than the first one but less accurate, which slightly reduces the overall performance of the system.

Authors in [5] compare position measurement techniques using dead reckoning for pedestrian usage. All employed techniques are step-based and use pedometers or accelerometers to measure steps and compass or rate gyroscope to determine the heading.

The indoor tracking system proposed in this work is designed to run on mobile devices making use of their built-in inertial sensors (3D accelerometers and compass). Since mobile devices with such capabilities are readily available to the market, this system can be considered as a low cost one. In order to provide an interactive user interface to the indoor tracking solution, a user friendly mobile application that implements a simple pedometer method is used. Even with all intrinsic device restrictions, a successful algorithm might promote new services and products.

The paper is organized as follows: Section II presents the pedometer-based system design and implementation. Section III describes the indoor test scenario, parameters and assumptions. The results and performance assessment are presented and discussed in Section IV. Finally, the conclusions are presented in Section V.

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II. DESIGN AND IMPLEMENTATION OF THE PEDOMETER-BASED INDOOR TRACKING SYSTEM

Our real-time indoor tracking system is based on a simple pedometer model that counts each step a user takes by detecting the motion of the user's hips. It can record how many steps the user has walked, and thus the meters (distance = number of steps x step length). Our pedometer model uses inertial sensors (accelerometers), compass and software to count steps and to perform the real-time indoor tracking for users carrying mobile devices. Figure 1 shows the block diagram of this design.

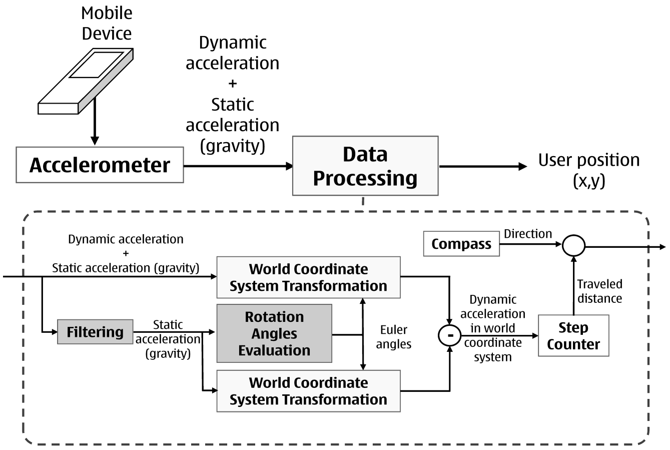

Fig. 1. Pedometer block diagram.

Basically, our pedometer approach gets the accelerometer readings (static + dynamic acceleration) in the device coordinate system and transforms them to the world coordinate system. In order to remove the static acceleration from the readings, a filtering and removal processing is required. After that, only the dynamic acceleration (caused by motions) is used to evaluate how many steps the user walked and then the traveled distance. Compass information is used for direction (azimuth) determination. Each block in the Figure 1 is more detailed below.

A. Accelerometer Block

The accelerometer block represents the acceleration readings collected from the mobile device in each axis of the device coordinate system (x_m, y_m and z_m). The measurements from accelerometers contain the gravity (static acceleration) and the acceleration caused by motions (dynamic acceleration).

B. Filtering Block

The main objective of the filtering stage is to extract the gravity from the raw data read from the accelerometers. The acceleration components measured by the device accelerometers contains the gravity and the acceleration caused by motions. In order to remove the acceleration caused by motions, the measured acceleration is filtered trough the low-pass finite impulse response (FIR) filter. FIR filter was chosen because of its stability and linear phase (i.e, it does not distort the phase of the input signal). Although it requires more processing than an Infinite Impulse Response (IIR) filter, the extra computational cost is not a problem because this stage is not the system bottleneck. The cut off frequency is set to $1Hz$.

C. Rotation Angles Evaluation Block

The purpose of this stage is to evaluate the mobile device orientation in terms of pitch (θ) and roll (ϕ) angles (Euler angles) related to the World Coordinate Systems (x_w, y_w and z_w). These angles can be estimated from gravity values in the Device Coordinate System (x_m, y_m and z_m). Figure 2 shows the definition of the Euler angles.

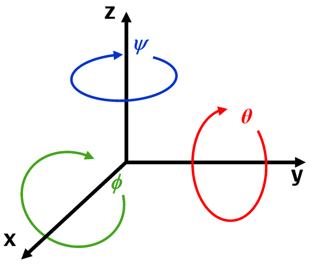

Fig. 2. Rotation angles.

The pitch (θ) and roll (ϕ) angles can be evaluated as [6]:

$$\theta = -arctan2\left(g_x, \sqrt{g_y^2 + g_z^2}\right) \quad (1)$$

$$\phi = -arctan2\left(-g_y, sign(\cos\theta), -g_z sign(\cos\theta)\right) \quad (2)$$

where g_x, g_y and g_z are the gravity acceleration components measured by the accelerometer in each axis, respectively. Pitch (θ) is defined as the rotation angle about the y_w-axis and roll (ϕ) as the rotation angle about the x_w -axis, both in clock-wise sense. The $arctan2(\cdot)$ function is the four-quadrant inverse tangent and $sign(\cdot)$ is the function that extracts the sign of a real number. It is noteworthy to mention that the equations above are valid only if $\theta \in [-\pi/2, \pi/2]$; otherwise, it is necessary to adjust the equations to cope with this change in the pitch angle.

D. World Coordinate System Transformation Block

This block transforms the device acceleration readings (collected in the device coordinate system) in world coordinate system. Figure 3 shows the concept about the device and world coordinate systems.

The transformation of the system's device-to-world coordinates can be performed as follows:

$$\mathbf{a}^w = \mathbf{R}_m^w \mathbf{a}^m \quad (3)$$

where $\mathbf{a}^w$ is the acceleration vector in the world coordinate system, $\mathbf{a}^m$ is the acceleration vector in the device coordinate system and $\mathbf{R}_m^w$ is rotation matrix to transform the device coordinate system into the world one, given by [6]:

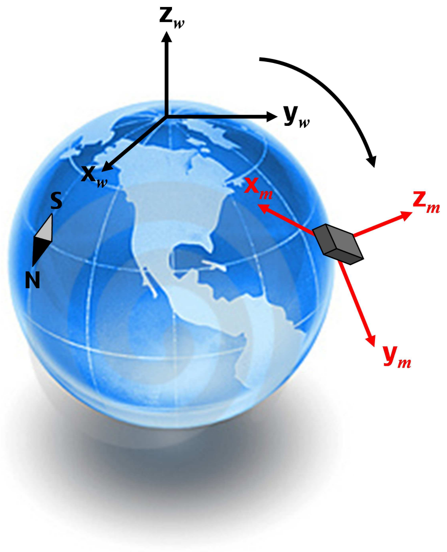

Fig. 3. Device and world coordinate systems.

$$\mathbf{R}_m^w = \begin{bmatrix} c_p.c_y & -c_r.s_y + s_r.s_p.c_y & s_r.s_y + c_r.s_p.c_y \\ c_p.s_y & c_r.c_y + s_r.s_p.s_y & -s_r.c_y + c_r.s_p.s_y \\ -s_p & s_r.c_p & c_r.c_p \end{bmatrix} \tag{4}$$

where $c_p = \cos\theta$, $s_p = \sin\theta$, $c_r = \cos\phi$, $s_r = \sin\phi$, $c_y = \cos\psi$, $s_y = \sin\psi$ and ψ, θ, ϕ being the Euler angles, i.e., yaw, pitch and roll ones. Here, yaw (ψ) angle may be ignored because it is not possible to obtain it from the information which is provided by gravity and, for convenience, it is set to zero. Due to that, $\mathbf{a}^w$ is equivalent to an acceleration vector in world coordinate system with x-component pointed to the north, y-component to west and z-component to up. The correct direction (azimuth) with respect to north is provided by the compass block and it will be explained afterwards in this section.

E. Step-counter block

This block intend to count the number of steps that are taken by the user, and thus the traveled distance (distance = number of steps x length). Our approach for step-counter is based on an heuristic proposed in [7], which compares mean values of acceleration samples and it is able to detect the user steps. The acceleration samples from a walk follows a pattern, composed of periodic maximums and minimums, as shown in the Figure 4.

The process of step detection consists of a comparison between values that are provided by three different sliding windows. Each sliding window is composed of a certain number of samples that are given by the accelerometer. There is an external window which is composed of η samples, an internal window (called previous window) with the $\eta/2$ initial samples and another internal window (called next window) with the $\eta/2$ final samples. Figure 5 shows an example of the mentioned sliding windows.

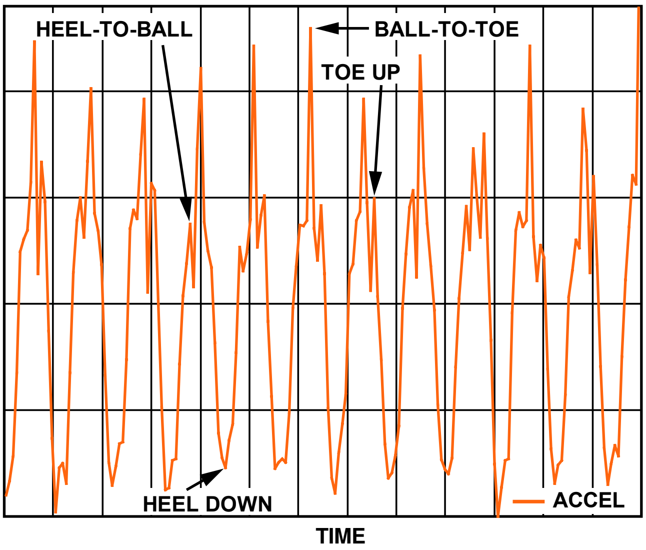

Fig. 4. Acceleration samples during a walk [7].

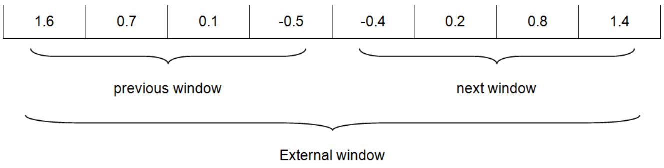

Fig. 5. Sliding window example

The acceleration at any given time is considered to be decrescent if the average of the first set of samples (previous window in Figure 5) is higher than the average of the external window samples plus a threshold and the average of the second set (posterior window in Figure 5) is less than average of the external window minus a threshold. The reverse comparison detects a crescent acceleration and a sequence of samples with crescent acceleration followed by decrescent one is considered a step.

Both the number of samples (η) of the sliding window and the threshold are established experimentally as a function of sampling rate and the dynamic range of the accelerometer in use.

In our approach, the dynamic acceleration information on the y- and z-axes, in the world coordinate system, are combined (added) and taken as input to the step-counter block. The objective is the reduction of the "false step" counting and, consequently, the improvement of the system's accuracy. It is important to mention that this step counter algorithm may provide erroneous information in the absence of movement if it interprets the noise of the sensors as real steps. In order to solve this issue, the standard deviation of the samples is compared with the latest samples to determine if the person is not walking. If so, the step counter algorithm is even not executed. This technique is simple, fast and presents satisfactory results.

F. Compass block

The purpose of the compass block is to determine the real direction (azimuth) of the user with respect to the Earth's North Pole in each instant. As the step-counter block provides only the total traveled distance, the compass outputs in each instant is than used to determine the traveled distance in each axis (x, y and z), and thus, to user positioning and tracking.

G. Indoor Tracking Application

The application in the mobile device was developed using the Qt platform [8], which includes Qt framework and tools, combined with tools that were designed to streamline the creation of applications for Symbian and the Maemo platform. Along with that, we used the S60 Sensor Framework [9], which is a Symbian C++ API that provides a consistent method of accessing the sensor hardware.

Along with the tracking application, two other modules were implemented: (1) step length configuration module and (2) accelerometer calibration module. The first one allows users to configurate their step length, parameter which is used by the step-counter block and has an important role in the tracking accuracy. The later is responsible for determining the accelerometer scale factor and zero-gravity offset in each trial [10]. The offset value can vary from device to device due to trim errors, mechanical stress and temperature changes [11].

There is also a need to include into the application the georeferenced map of the environment where the trials are intended to be executed.

Figure 6 shows a snapshot of our application running on Nokia N97 device.

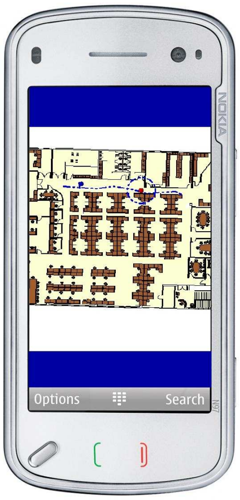

Fig. 6. Snapshot of the real-time indoor tracking application.

III. TEST SCENARIO, PARAMETERS AND ASSUMPTIONS

In order to evaluate the performance of the proposed real-time indoor tracking system, it was considered as case study the scenario shown in Figure 7. This scenario represents the Nokia Institute of Technology (INdT) floor inside of the Nokia's building in Manaus city (Brazil). The main parameters and assumptions used in our experiments are listed in Table I.

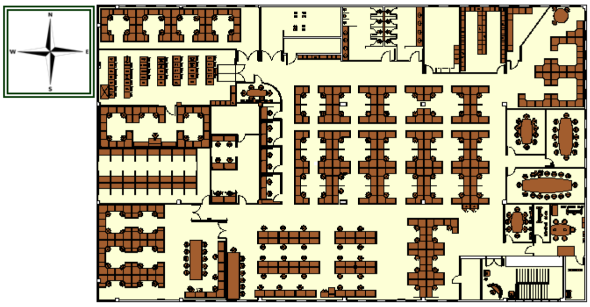

Fig. 7. Test scenario in INdT office.

TABLE I

MODEL PARAMETERS AND ASSUMPTIONS

Parameter	**Value**	**Unit**
Device model	Nokia N97	-
Sensors sample rate	38	Hz
Sliding window length	8	$samples$
Step length	80	cm

IV. REAL-TIME INDOOR TRACKING RESULTS ON MOBILE DEVICES

The pedometer-based real-time tracking model was tested under the scenario of Figure 7. Optimal values for the parameters (filter, sliding-window size, step thresholds, etc) were extracted from experiments with about 10 persons performed in several environments. Personal characteristics as gender, height, weight, speed walking and footwear were taken into account in the parameter evaluation process. For all cases, the optimized values found produced similar behavior for the system accuracy performance.

One of the main issues that affects the performance of the application is related to the information that is obtained from the built-in compass. This information may become distorted when the mobile phone is close to other electronic devices (such as notebooks and printers) that generate electromagnetic interference. In addition to this problem, the compass of the mobile phone suffers from hysteresis that introduces systematic errors on the readings. For this reason, it has to be calibrated from time to time in order to increase the accuracy.

Figure 8 shows the screenshot of the mobile phone and the performance of the application can be observed. In this figure, the red square represents the actual walking path where the person walks in a clockwise manner, starting at the upper left corner of the red square. The blue dashed lines represent the path that was estimated by the pedometer model. It is clear from this result that the hysteresis effect suffered by device compass influences the final result. Despite this fact, the maximum error in this situation was around 3.5 meters.

Other important parameter that impacts the performance of the pedometer-based approach is the step length. Figure 9 shows the impact of this effect on the same walking path of the Figure 8 but considering a step length of 70 cm. The position estimation was good at the beginning but during the walk the person took steps shorter than the step length that was configured in the application. This fact resulted in estimation errors at the final part of the walk.

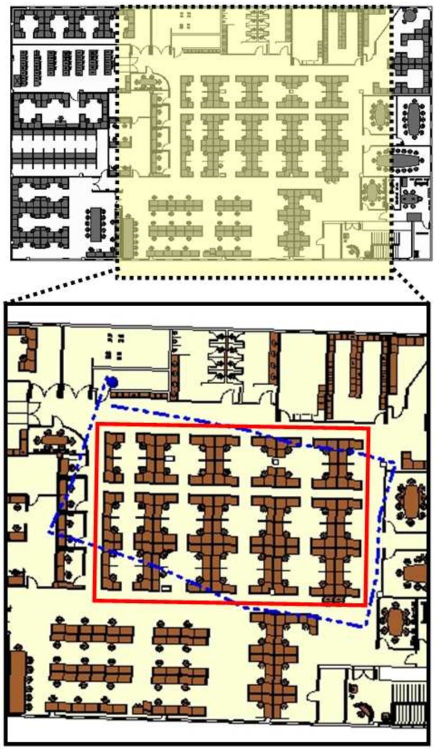

Fig. 8. Experiment 1: Interference effect on the device compass.

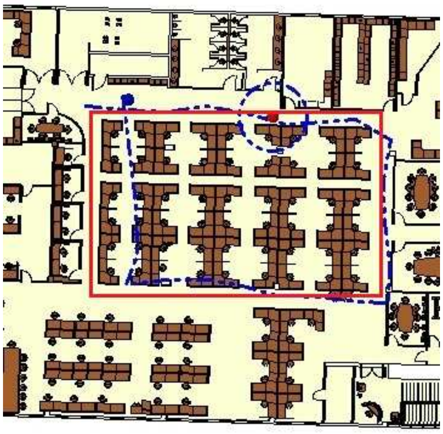

Fig. 9. Experiment 2: Dependency on the step length.

Regarding the performance of the accelerometers, our solution can be robust against some of the noisy effects generated by these sensors. This robustness is achieved because the our pedometer-based system depends only on the variations of the acceleration, not on its absolute values of it.

On the other hand, tracking accuracy is very dependent of the information provided by the compass, correct definition of the step length and the correct step counting parameters.

In addition, there are several intrinsic limitations concerning pedometer, such as:

- people tracking only because of the walking movement (not applicable for vehicles for instance);
- step rate for correct detection depends on the sensor sample rate and sliding window length. For the system deployed in this paper, i.e., sensor sample rate of 38 Hz and sliding window lenght of 8 samples, the theoretical limit for correct step detection is 38 / 8 = 4.75 steps/s.
- requirement of a customized step length definition for each person;
- false step counting;
- cumulative errors.

V. CONCLUSIONS

We have described the implementation and evaluation of a low-cost pedometer-based system for real-time indoor tracking on mobile devices. The performance evaluation of our approach show that the proposed solution is not a mature technology yet, being very dependent on the quality of the sensors. Current mobile devices such as Nokia N97 have low-cost sensors, presenting low tolerance to noise and electromagnetic interference. Even though the accuracy of our model is considered moderate compared to the other solutions in the literature, our system is very simple, easy to deploy and does not require high costs with infrastructure and/or acquisition of extra equipments in order to provide indoor tracking.

As the research continues, new solutions will be evaluated as well as alternatives to the pedometer approach. Comprehensive solutions for the indoor tracking problem are extremely important, because they are applicable for situations when GPS signal is unavailable or when similar applications which seek accurate supplements to GPS.

Future works will be focused on the accuracy improvement of our approach with the use of data filtering and interference reduction strategies.

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