Traveled Distance Estimation Algorithm for Indoor Localization

Rui Terra, Lino Figueiredo, Ramiro Barbosa, Ricardo Anacleto

Abstract

This paper presents an ankle mounted Inertial Navigation System (INS) used to estimate the traveled distance. The number of steps is used to estimate the travelled distance. The propose method is based on force sensors to enhance the results obtained from an INS. Experimental results have shown that, depending on the step frequency, the travelled distance error varies between 2.7% and 5.6%.

Keywords

Inertial Navigation System; Pedestrian Dead Reckoning; Step Frequency; Step Length Estimation.

1. Introduction

The ability to locate an individual is an increasing need for various purposes, for instance, healthcare, tourism, safety, etc. Existing outdoor localization systems are relatively accurate and easy to access, and are available on any recent mobile device. However, in dense environments (forests, urban canyons) or indoors these localization systems are not functional.

Several navigation systems for indoor environments have been developed using technologies such as Radio Frequency Identification (RFID) [1][2], InfraRed (IR) [3][4], ultrasound [5], Bluetooth beacons [6][7], bar code[8], among others. [9] The main problem of such systems is that they need a structured environment to determine user location. This makes the systems context-dependent, impractical and expensive to implement. Thus, if it is desired to obtain location indoors without the need of a structured environment another solution must be found.

The Inertial Navigation (IN) is a localization technique in which the values obtained by inertial sensors (accelerometers and gyroscopes) are used to estimate the location and orientation without requiring external references. The use of an Inertial Navigation System (INS) for estimating the successive displacements in conjunction with the technique Dead Reckoning (DR), allows estimation of the current location based on an initial one. DR is a navigation technique that adds successive displacements to a known position to estimate the current position.

The main propose of this paper is to describe our work that estimates the traveled distance in indoor environments.

This work is our first step to develop an INS to continuously calculate, using DR, the position, orientation and velocity of a person in indoor environments without using any structured environment.

In this paper we present the study and the developed approach to estimate the traveled distance based on the number of steps, i.e., our approach to estimate the travelled distance based on the step frequency.

To study the human locomotion and implement the referred approach, it was developed a hardware module to gather step information and send it by Bluetooth to a smartphone or a computer.

The aim of this study is to develop an algorithm to estimate the travelled distance, in real time, with the smallest possible error through the step frequency. To do that we used a step counting algorithm with a small counting step error that require low computational power;

This paper is organized as follow. The basic principles of inertial navigation are given in section 2. In section 3 a detailed description of the developed INS is provided. Section 4 presents the approach to estimate the traveled distance by the step cadency, and the tests carried out to attest the accuracy of the studied and developed approaches. Finally, section 5 provides the conclusions and future work.

2. Inertial Navigation Systems

The INS hardware consists of a processor unit and an Inertial Measurement Unit (IMU). An IMU is a unit with inertial sensors accelerometers and gyroscopes.

The INS are divided into two categories: the Gimballed INS and the Strapdown INS. These systems obtain the measurements in different frames. The frame that is attached to the IMU is the sensor frame and the reference frame is the navigation frame.

In the Gimbaled INS the sensors are in a platform that mechanically stabilizes the system. In this type of INS the sensors are mechanically isolated from the rotational movements. This is possible because gyroscopes detect the platform rotations and the gyroscope signals are feedback to the motors in the rotation axis to cancel the rotations and maintain the system stabilized in the navigation frame. As a consequence, the accelerations are obtained directly in the navigation frame. In other words, the sensor frame is mechanically placed in the navigation frame.

In the Strapdown INS sensors are fixed to the system to be tracked and rotated with it. In this case the accelerations are obtained in the coordinate space of the IMU (sensor frame). This fact brings a mathematical complication, since accelerations are not in a coordinate system easily associated with a room or user space (navigation frame). To obtain the acceleration in the navigation frame it is necessary to mathematically transform the accelerations from the sensor into the navigation frame. [10][11][12][13][14][15]

The mechanically stabilized systems are big and expensive, [16] making them impractical to be used by people to estimate the distance traveled on foot.

The Micro Electro Mechanical Systems (MEMS) enabled many emerging applications. MEMS technology offers many benefits such as: size, cost, and power reduction. However, the reduction in size of the sensing elements creates challenges for achieve good performance. In general, with the decrease on size, the sensitivity (scale factor) decreases, noise increases, and driving force decreases. [17]

MEMS accelerometers and gyroscopes are being assembled in tiny, inexpensive and robust IMU allowing them to be used by persons comfortably in order to monitor the human movement. [18]

To estimate the traveled distance of a Pedestrian there are several methodologies. Harle [19] states that the simplest approach to estimating traveled distance is to assert the step length as constant. However, this approach is only valid if the pedestrian adopt their natural walking step.

Harle [19] states that an alternative is to estimate the traveled distance based on the step frequencies. The step frequency can be estimated using step detection algorithm similar to [20] or [21]. Zhao [21] developed a set of relationships to estimate the step length based on the step frequency. These relations will be studied in this paper.

Direct measurements of the step length have also been used. [19] Several different systems have been developed in the past years. These systems use different locations in the human body to place the sensors. There are many INS that placed the sensors on the waist or on the foot. [22]

Langer et al. [23] developed a GPS/INS pedestrian navigation system to improve position accuracy and availability in weak GPS signal conditions. The system is a torso mounted IMU used for step detection, step length and heading estimation. They also use other sensors like barometer and magnetometer. [23]

Goyal et al. [24] presents a waist mounted DR System. This system is an IMU with a magnetometer. They obtained an average relative distance error of 3 to 8% in indoor environments. [24]

Judd et al. discussed a range of tests for DRM4000 system from Honeywell in [25], with special attention to indoors. The authors state that the characteristics of the module error are time independent and primarily dependent on the traveled distance. According to the experiments performed in a calibrated unit the error is approximately 2% of the distance traveled for level sidewalks and 5% for grassy hills. They concluded that the best location for the module is centered on the lower back.

The NavShoe [26] is a hybrid system consisting of an INS in the foot and a GPS in the body. The authors indicate that the system has an accuracy of 0.3%.

Nilsson et al. [27] presented a foot-mounted INS. The author’s claim that the performance evaluation of the system shows position errors for short trajectories (< 100 m) of ± 0.2-1 % of the traveled distance, depending on the shape of trajectory.

Bird et al. [22] developed a foot-mounted INS embedded with a magnetometer, and a GPS receiver on the shoulder. They presented an algorithm in which the resulting estimated track stays within about 2 m of the true track (about 100 m) throughout the entire indoor run.

The foot-mounted approaches allow to precisely detecting the gait phases. This is very important since these approaches are recursively integrating the data from the inertial sensors. The errors from the inertial sensors are also integrated generating accumulative errors over time. [9] So, detecting the instants when the foot is stationary in the ground enables the application of assumptions to control the errors. The application of these assumptions consists in forcing the system to an expectable behavior in a specific situation. For example, when the foot is stationary on the ground the velocity should be zero by forcing the velocity to zero the position in these moments doesn’t diverge. This is a key concept to control the step length estimation error and is designated of Zero velocity UPdaTing (ZUPT). Using these kinds of assumptions the position error growth can be reduced. [28]

3. Foot INS module Architecture

A hardware platform was developed to study the human locomotion and test the algorithms to estimate the travelled distance. The developed INS is a modular system which allows the study of different navigation algorithms in conjunction with different sensors.

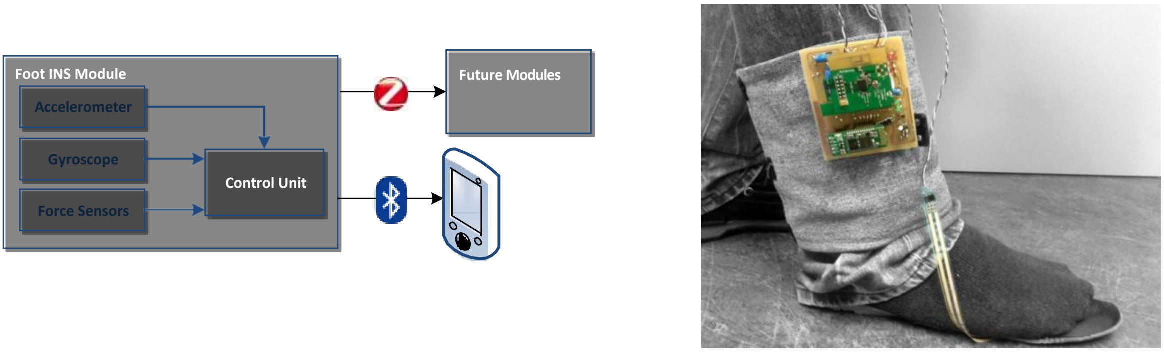
The developed INS module is presented in figure 1 a). This is constituted by an ADXL345 accelerometer from Analog Devices, a L3G4200D gyroscope from STMicroelectronics and two A201 force sensors from Tekscan.

The accelerometer and gyroscopes are used to have a complete detection of the movement. The accelerometer measures the linear accelerations and the gyroscope measures the angular velocities.

The force sensors were added because we believe that the information gathered by force sensors can be used to develop computationally light algorithms and will allow us to reduce the inherent errors of the INS.

This INS module developed contains two communication interfaces: Bluetooth to communicate with a smartphone or a computer, and ZigBee to communicate with future modules that will be included in the system, for instance, a module in the waist to estimate the orientation.

The developed INS module is placed on the user ankle. In figure 1 b) is presented the developed system on the user ankle connected to one of the force sensors.



a) b)

Figure 1. a) Developed INS; b) Position of the INS on the human body

4. Traveled distance estimation based on the number of steps

To estimate the traveled distance through step cadency it was first necessary to estimate the number of steps.

4.1. Step Counting Algorithm

The first step counting algorithm that we have used (proposed by [20]) calculates the steps based on acceleration of the ankle. To distinguish more accurately the step stages we have added the analysis of the force that is applied on the foot plant [18]. To obtain the plantar force, two force sensors (A and B) were used and were disposed on the foot as represented in figure 2. Figure 2 also presents the force distribution in the foot (represented in gray) during locomotion [18].

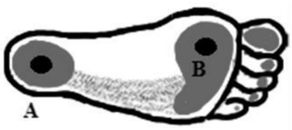


Figure 2. Sensor Position and Applied Force

These two places (A and B) were chosen because in the initial phase of walking the first contact of the foot on the ground is where sensor A is placed, and in the final phase, which represents the foot last contact with the ground, is where sensor B is placed. However, when the user is running the force is almost all on the front of the foot. [18]

On figure 3 is represented the data gathered by INS module for an experiment of ten steps in a straight line. The solid line represents the acceleration of the ankle, the dashed line represents the data from force sensor A and dotted line represents the data from force sensor B.

As can be seen the values of force are zero, or almost zero, when the foot is moving (when there is higher variations in acceleration values), and when the foot is on the ground, sensor A goes first to a high value and then sensor B goes to a high value, as expected.

Figure 4 presents the step count algorithm. First a low pass filter is applied to the acceleration data and a threshold filtering applied to the force data.

The next phase consists in combining the data from the two force sensors into one. In this phase the final force sensor data will be different of zero when a force is applied to the heel until no force is applied in the front of the foot. If the final force is not zero the acceleration is defined to a predefined value of 1g, and the threshold to the minimum value. If the final force data is zero the acceleration threshold is computed and compared with the real acceleration to estimate the number of the steps. The number of steps is equal to the number of times that the acceleration is greater than the threshold. More information about this algorithm can be seen in [29].

To test the algorithm it was carried out ten experiments with ten steps each in three types of locomotion (standard walking, fast walking and running), and five experiments of one hundred steps in the same types of locomotion. In table 1 we present the average errors for all experiments. Considering the 10 step tests the results are very similar for each type of walking. In Standard and Fast Walking there are no errors in the step calculation. In Running there are errors, however this situation is the most stressful for the system. Nevertheless these errors reduce over the time, as it can be seen in the 100 step tests results. The results have shown that our algorithm is equal or better in a long term use.

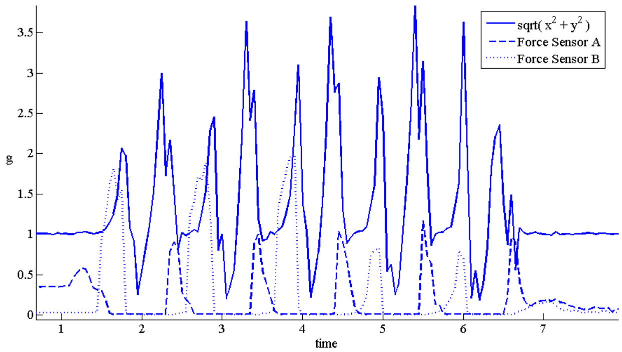


Figure 3. Acceleration and Force data from a ten step test

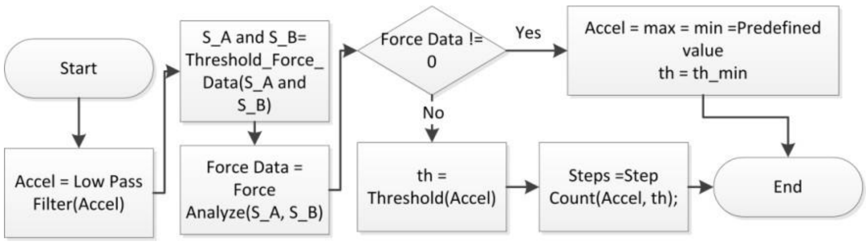


Figure 4. Algorithm to estimate the number of steps

In our approach the threshold and step analysis is only computed if the data from the force sensors is zero and only stores the actual computed acceleration and the actual threshold. In other words our approach is computationally light.

Table 1. Errors for a 10 and 100 step tests

	Standard Walking	Fast Walking	Running
10 steps	0%	0%	1%
100 steps	0%	0%	0.4%

4.2. Length estimation

Harle [19] states that the simplest approach in order to estimate the step length is to consider it as constant, because the pedestrians have a step length near to constant when they adapt their natural walking pace. An alternative is to estimate the step lengths based on the step frequencies, which can be estimated using the step detection techniques similar to the ones that we have developed.

In this approach to estimate the travelled distance we use the equation (1). This equation obtains the travelled distance using the distance per step based on the number of steps per period (speed).

$$\text{Trav.Dist.} = \text{number of steps} \times \text{distance per step} \quad (1)$$

In order to estimate the distance per step, Zhao [21], used relations proportional to the user height. As Zhao states the step length would be longer if the user is taller or running at higher speed.

Initially we have used as reference the relations, presented on table 2, from the study of Zhao [21], where the distance is updated every two seconds.

Table 2. Step length as a function of Speed (steps per 2 seconds) and Height [21]

Steps per 2 s	Step Length (m)
1	Height/5
2	Height/4
3	Height/3
4	Height/2
5	Height/1.2
6 or 7	Height
>= 8	Height×1.2

The distance per period (2 seconds) is obtained based on table 2, and the total distance is obtained through DR.

To test this approach we have done several tests in straight line in a known distance (10 meters). The tests were made, once more, in the three types of locomotion (standard walking, fast walking and running). The tests were made in a user of 1.80 meters of height and we obtained errors of 16.4%, 54% and 50.43% for standard walking, fast walking and running, respectively.

It should be noted that the errors obtained with the calculation of steps directly affects the distance traveled and, once we are using an iterative process (Dead Reckoning), the inaccuracies in the estimation of the distance results are cumulative errors over time. On the other hand, the errors obtained in the step count algorithm have shown that our algorithm has a small error and tend to be smaller in a long term use.

In order to obtain results with a smaller error we have tuned the Zhao [21] approach, which result in table 3.

Previously to tune the Zhao approach we have tested other periods (smaller than 2 seconds) in order to obtain a period that could lead to a smaller error. After several tests we have concluded that the 2 second period, as in the Zhao approach, is a good period because with periods of 0.5 seconds we couldn’t distinguish between the three types of locomotion; and with periods of 1 second we couldn’t distinguish between fast walking and running. However, with the 2 second period it’s possible to make that distinction.

The main differences between our approach and the Zhao are that we don’t consider if the user gave one step per 2 seconds because we consider that when someone just took one step in 2 seconds it doesn’t meant that the user is moving from one side to another but just changing the position or orientation themselves; we use the same distance per step if the user gave 2 or 3 steps; and the remaining parameters we have tuned for our user.

We analyzed the data from the previous tests in our tuned approach and obtained an error of 4.04%, 2.68% and 5.59% for standard walking, fast walking and running, respectively. It should be noted that these tests were obtained from a user of 1.80 meters of height.

Table 3. Step length as a function of Speed (steps per 2 s) and Height (tuned)

Steps per 2 s	Step Length (m)
2 or 3	≈ Height/3
4	≈ Height/2.5
5	≈ Height/2
>=6	≈ Height/1.5

4.3. Results Analysis

In the table 4 are presented the errors obtained from the two approaches. It's noteworthy that the data and the step calculation algorithm are the same, the only difference are the relations. After the tuning the error decreased dramatically.

Table 4. Distance Estimation Error based on step frequency

	Standard Walking	Fast Walking	Running
Neil Zhao	16.4%	54%	50.43%
Our approach	4.04%	2.68%	5.59%

Based on our study these approaches shown to be very user dependent, and the relation presented here was only tested in one user so, with other users we may not have the same results. Although the results after tuning are interesting we don't take this approach as a reference, because:

- Two users with the same height might have different leg length, resulting in a different step length.
- To obtain estimated distances with acceptable errors it is necessary to tune the relations for each user.

5. Conclusions and Future work

In this paper we propose a method based on force sensors to enhance the results obtained from an INS. The number of steps is used to estimate the travelled distance. The errors to estimate the number of steps are null or small, so this will not have a big effect on the travelled distance error. The Zhao [21] approach shown to be very interesting since we have confirmed that the concept, after tuning, can lead to acceptable results in several walking cadences (smaller than 6%). However this approach shows to be very user dependent, nevertheless the errors decreased dramatically if we tune the system for a specific user.

Since these kind of approaches are very user dependent we are currently working in other direction. We pretend to estimate the traveled distance by mathematically integrate the acceleration obtained by the IMU.

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