Orientation Analysis through a Gyroscope Sensor for Indoor Navigation Systems

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***Abstract*— Last years have been characterized by an incredible growth in mobile computing capabilities and sensing technologies, which can leverage the deployment of many location-based applications, ranging from pedometers to navigation system. This work deals with an Inertial Navigation System (INS) able to support users in the navigation in an unknown indoor environment by continuously calculating their motions and their position. The proposed solution is based on integrated use of movement and position sensors. Unfortunately, applications that rely on the use of measures coming from orientation sensors, such accelerometers and digital compasses, are affected by external magnetic interferences thus resulting in inaccurate directional information. This paper focuses on this problem by investigating the use of the gyroscope as the primary determinant of orientation. Several tests have been carried out showing how the proposed method is able to correct the error introduced by the gyroscope both in static position and undergoing rotation, and thus, it is able to provide better orientation information than the compass.**

Keywords-pedestrian navigation; rotation sensors; gyroscope; digital compass; indoor navigation.

I. INTRODUCTION

Nowadays, modern mobile devices, such as smartphones and PDAs in general, come to the market already equipped with sensors able to track them as they move, both in outdoor and in indoor environment. The sensing technologies embedded in such devices make it ideal for a wide range of location-based services, such as navigation applications.

An Inertial Navigation System (INS) uses motion and rotation sensors in order to determine the position, orientation, and velocity of a moving object/user without the need of external infrastructures [1]. This is essential in an indoor environment where common localization systems, such as Global Positioning System (GPS), fail due to severe attenuation or obscuration of the satellite's signal. In inertial navigation systems, localization/orientation estimation is source-independent. The user's position is calculated in relation to a known starting position using a dead reckoning algorithm and the orientation is usually provided by a digital compass embedded in the smartphone. A digital compass sensor provides the orientation of the device relative to the magnetic north of the earth. However, when used in indoor environments, like any magnetic device, it is affected by significant error caused by nearby ferrous materials, as well as local electromagnetic fields. Such errors seriously affect the performance and the accuracy of the system, thus the need to investigate any alternative orientation technique.

The present paper focuses on this problem by investigating the use of a gyroscope for navigation in indoor environment. A gyroscope is a device for measuring or maintaining orientation, based on the principles of angular momentum. The paper is organized as follows: in the next section, we describe the background and related works in the field of indoor navigation systems. Section III provides an overview of the developed application and presents the system architecture. Then, in Section IV, the gyroscope's functionalities are presented and in the next section the gyroscope calibration procedure is described. In Section VI, a comparison between gyroscope and compass behavior is analyzed, and finally, we draw the conclusion in the last section.

II. RELATED WORK

Most mobile navigation systems rely on the use of the digital compass embedded in the smartphone. It is proved that the measurements provided by this sensor are affected by large error, due to the existence of metallic objects and magnetic fields that often compromise the reliability and accuracy of the system. To compensate compass errors, many efforts have been made exploiting different approaches. As experienced by King et al. [2], the measurement errors can vary a lot through the test environment, even if they calibrated the compass in the middle of the operation area. A variation of 1° is measured near the point of calibration, but variations up to 23° are detected a few times in certain points, always close to electromagnetic objects and electronic devices.

Sun et al. [3] proposed a novel approach to provide reliable orientation information for mobile devices in indoor environments that is not affected by magnetic interferences. Pictures of the ceiling of indoor environment are aggregated and computer vision based pattern matching techniques are applied in order to utilize them as orientation references for correcting digital compass readings. Ladetto et al. [4] develop a wearable dead reckoning unit consisting of gyroscope, compass and accelerometer, but they only use the gyroscope for correcting the compass heading errors due to magnetic interferences. In a later work, a pedestrian navigation system was proposed by Ladetto and Merminod [5]. They show that coupling a magnetic compass with a low-cost gyroscope in a decentralized Kalman filter [6]

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configuration can limit the errors in the determination of the azimuth of walk. In non-magnetically disturbed areas, the results are close to each other and errors in position are limited. The addition of a gyroscope helps bridging the gap when the compass is strongly disturbed and improves the reliability of the system. Hoshino et al. proposed an extended Kalman filter to combine a magnetic compass and a rate gyroscope for sensor errors compensation [7]. A mathematical model for magnetic compass errors caused by body magnetization is proposed as well as an error model of the rate gyroscope. Barthold et al. [8], exploit the built-in gyroscope in the Nexus S smartphone to address the interference problems associated with the orientation sensor. Many tests were carried out and they proved that integrating the angular velocity output of the gyroscope allows predicting angular orientations to within 6% for test rotations, as well as detecting turns while the phone's orientation was constantly changing. A study to investigate if and how magnetic sensors can be used to replace gyroscopes is conducted by Kunze et al. [9], showing a method to compute angular velocity from 3D magnetic sensor data and discussing its fundamental limitations.

III. APPLICATION FOR INDOOR NAVIGATION SYSTEM

In the context of Indoor Navigation System, we have developed an early prototype of a pedestrian navigation system for indoor environments based on dead reckoning, 2D barcodes and data from accelerometers and magnetometers. All the sensing and computing technologies of our solution are available in common smartphones [10].

The prototype has been further improved by a new algorithm described afterwards (Section V) and now it is able to estimate the correct current position of the user, track him inside the building and provide the best path to achieve a specific destination [11].

The application does not need to connect to any external or pre-installed positioning system such as GPS or Radio Frequency IDentification (RFID), or to use Wireless Fidelity (Wi-Fi) trilateration. The prototype of the proposed system uses just the data from the motion sensors embedded in the smartphone to compute the correct position of the user based on a known initial location, combined with a reference map of the building.

A. *Functionality*

The initial position of the user, the only certain information on which the system relies on for further calculation, is retrieved by scanning and decoding a geo-referenced datamatrix (2D barcode), placed inside the building, using the built-in camera of the smartphone. Based on the URL encoded in the datamatrix, the application downloads from a dedicated server the indoor vector map for the specific floor, the initial position of the user on the map (corresponding to the point where the user stands when scanning the datamatrix) and a database that stores information about the setup of the building. When the user starts walking, the application draws step by step his position over the downloaded map of the building floor.

The user's position is calculated in relation to a known starting position using a dead reckoning algorithm. In the specific, the application tracks the number of steps taken by the user based on the linear numerical values returned by the smartphone's accelerometers. The acceleration value is the modulus of the accelerations registered in the x, y and z-axes. One step is detected when this module is above a high threshold (*Th_high)* and successively is below a *Th_low* value. To determinate the orientation, only the gyroscope is used thanks to an algorithm of calibration widely described next.

IV. GYROSCOPE

A gyroscope is a device for measuring or maintaining orientation, based on the principles of conservation of angular momentum. It's used primarily for navigation and measurement of angular velocity up to 3 directions: 3-axis gyroscopes are often implemented with a 3-axis accelerometer to provide a full 6 degree-of-freedom (DoF) motion tracking system. There are three basic types of gyroscope:

- *Rotary gyroscopes* are typically composed by a spinning disk or mass on an axle, which is mounted on a series of gimbals; the gyroscope follows the law of conservation of angular momentum, which says that the total angular momentum of a system is constant in both magnitude and direction if the resultant external torque acting upon the system is zero [12];
- *Vibrating Structure Gyroscope* or Micro Electro-Mechanical System (MEMS) contains vibrating elements to measure the Coriolis effect, which states that an object with mass m moving with velocity v , in a frame of reference rotating at angular velocity ω , act a force F_c [13] in a direction perpendicular to the rotation axis and to the velocity of the body in the rotating frame:

$$F_c = -2m(\omega * v) \quad (1)$$

- *Optical Gyroscopes*: they operate on the principle of the Sagnac effect, but, due to the extensive amount of fibre-optic cable needed, optical gyroscopes are mainly used in naval and aviation applications.

Some basic specifications of a gyroscope sensor are:

- *Measurement range*: specifies the maximum angular speed that can be measured by the sensor, is typically expressed in degrees per second $[deg/sec]$;
- *Number of sensing axes*: to measure angular rotation, the gyroscope can uses one, two, or three axes. The spatial orientation of a rigid body is thus based on three parameters: *azimuth*, rotation around the z axis; *pitch*, rotation around the x axis; *roll*, rotation around the y axis, as shown in Figure 1;

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- *Working temperature range*: from -40˚C to between 70 and 200˚C;
- *Shock survivability*: specifies how much force the gyroscope can withstand before failing. Fortunately, gyroscopes are very robust, and can withstand a very large shock (over a very short duration) without breaking. Generally, this is measured in [g] (1g is the earth's acceleration due to gravity), occasionally is also given the time with which the maximum g-force can be applied before the unit fails;

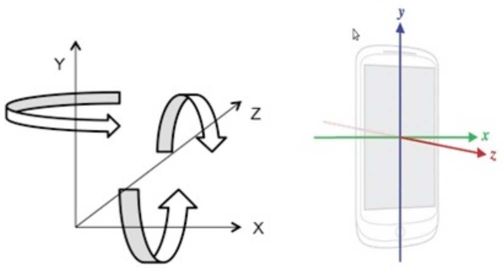

Figure 1. Axes and rotation angles of a smartphone: azimuth (z axis), pitch (x axis) and roll (y axis) parameter.

- *Bandwidth*: the bandwidth of a gyroscope typically indicates how many measurements can be made per second, thus the gyroscope bandwidth is usually intended in $[Hz]$;
- *Angular Random Walk (ARW):* this is a measure of gyroscope noise $[\text{deg/sec}]$;
- *Bias*: the Bias of a gyroscope sensor is the signal output when it is not experiencing any rotation. The Bias error can be expressed in [deg/sec]. A constant Bias error of ε, when integrated, causes an angular error which grows linearly with time:

$$\theta(t) = \varepsilon * t \tag{2}$$

The aim of this project is to examine the level of accuracy that can be achieved in positioning by using built-in sensors in an Android smartphone. The focus has been put on estimating the position of the mobile phone inside a building only using the gyroscope sensor to determinate the orientation through a specific algorithm of calibration described in the following paragraph.

V. Gyroscope calibration Alghorithm

To improve the gyroscope's accuracy we created an algorithm for both still and rotating devices:

- The first part is related to the Bias error when the device is not undergoing rotation. In this case, the constant Bias error of a gyroscope can be estimated by taking a long-term average of the gyroscope's output, which it would be null. Once the Bias is known, it will be subtracted from each value of the gyroscope's output. For this kind of test we have not used any particular equipment, but only the smartphone (Figure 2b) on the level.
- The second part is related to the Bias error when the device is moving.

The equipment used to calculate the real Bias error, when the device is undergoing rotation, is a Stepper Motor (Figure 2a), which converts electrical pulses into discrete mechanical movements. The tests were carried out with a smartphone Samsung Nexus S (Figure 2b). Table I shows the embedded sensors in the smartphone and the angular velocity set in the Stepper Motor.

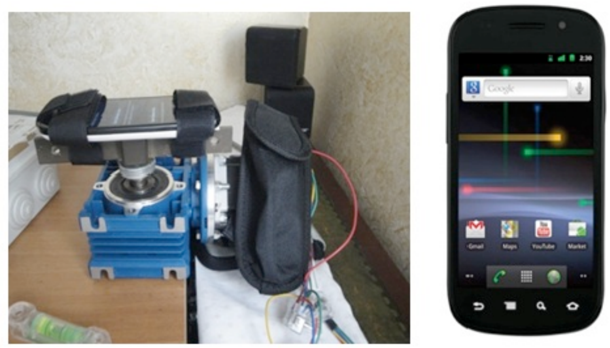

Figure 2. a) Stepper Motor; b) Samsung Nexus S.

TABLE I. Specification Equipment

Embedded sensors in mobile smartphone Samsung Nexus S			
Sensor type		***Manufacturer***	***Quantity Measured***
Accelerometer	KR3DM	STMicroelectronics	Acceleration
Gyroscope	K3G	STMicroelectronics	Angular velocity
Magnetic Field	AK8973	Asahi-Kasei	Magnetic Field
Stepper Motor			
Angular Velocity [rad/s]		0.307876080	

A. Drift Tests

The goal is to find a calibration method for the gyroscope, when the device is not undergoing rotations. In this case, the angular velocity along the three axis should be zero. We calculate the average error of the gyroscope's output along z axis. We have made 4 tests on 1,000, 5,000, 10,000 and 100,000 readings, each composed by 5 sessions (S). This way, we can evaluate how the gyroscope's output changes over time with a constant number of readings.

Table II shows that the average error of the angular velocity is similar for each test and it is independent from the number of readings.

TABLE II. Average angular velocity

Session	***Test 1 (1,000 r) μ(z)***	***Test 2 (5,000 r) μ(z)***	***Test 3 (10,000 r) μ(z)***	***Test 4 (100,000 r) μ(z)***
1	-0.00344	-0.00310	-0.00317	-0.00337
2	-0.00321	-0.00329	-0.00328	-0.00361

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3	-0.00331	-0.00330	-0,00341	-0.00359
4	-0.00344	-0.00374	-0.00373	-0.00375
5	-0.00290	-0.00288	-0.00291	-0.00319
μ/5	**-0.00326**	**-0.00326**	**-0.00330**	**-0.00350**

The gyroscope's error is completely random and it does not follow a specific error model. For this reason we assume that the Bias is equal to the average error on 1,000 readings. Figure 3 and Figure 4 show how the calibration algorithm improves the accuracy of the output of the gyroscope by subtracting the Bias from each reading.

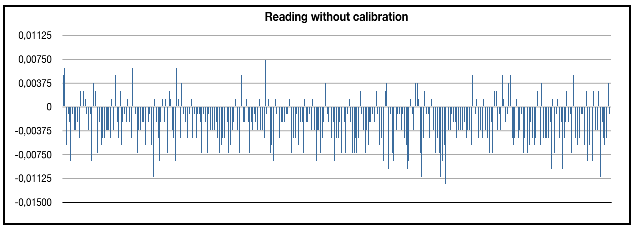

Figure 3. Acquired values from gyroscope without calibration (1,000 readings)

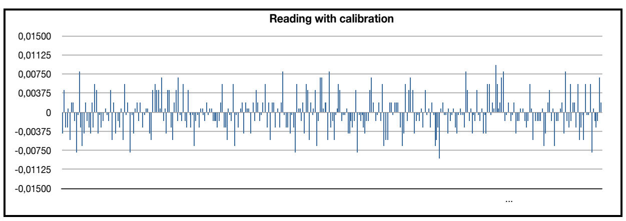

Figure 4. Calibrated values of the gyroscope computed by subtracting the Bias error from each reading (1,000 readings)

B. Rotation Tests

To evaluate the error of the gyroscope when the device is undergoing a rotation, a stepper motor is used. It has a constant angular velocity of 0.307876080 [rad/s]. We fixed the device on the stepper motor thus the gyroscope starts reading the angular velocity when the stepper starts moving. We have made three tests with different number of readings (1,000, 10,000, and 20,000). Each test has been done for 10 times as shown in the following Table III.

TABLE III. AVERAGE ERROR OF THE GYROSCOPE COMPARED TO ANGULAR VELOCITY OF THE STEPPER WHILE THE DEVICE IS UNDERGOING A ROTATION AND WITHOUT CALIBRATION

Session	**Moving Test without calibration**			
	Test 1 (1,000 r) μ(z)	***Test 2 (10,000 r) μ(z)***	***Test 3 (20,000 r) μ(z)***	***Stepper μ(z)***
1	0.310910783	0.310656723	0.311009743	0.30787608
2	0.308800393	0.311028093	0.311249073	0.30787608
3	0.310697943	0.310950093	0.311037773	0.30787608
4	0.310861703	0.310756913	0.311065993	0.30787608
5	0.310462643	0.310637243	0.310994773	0.30787608
6	0.309352843	0.310583343	0.311551243	0.30787608
7	0.308340043	0.311504683	0.311021863	0.30787608
8	0.308239443	0.310784043	0.311163783	0.30787608
9	0.310514923	0.310720443	0.310731343	0.30787608
10	0.307767003	0.311079643	0.311277343	0.30787608

As shown in Figure 5, the trend of the blue line, which refers to the 1,000 readings, shows how the average angular velocity acquired by the sensor is significantly different from the trend representing the reference angular velocity.

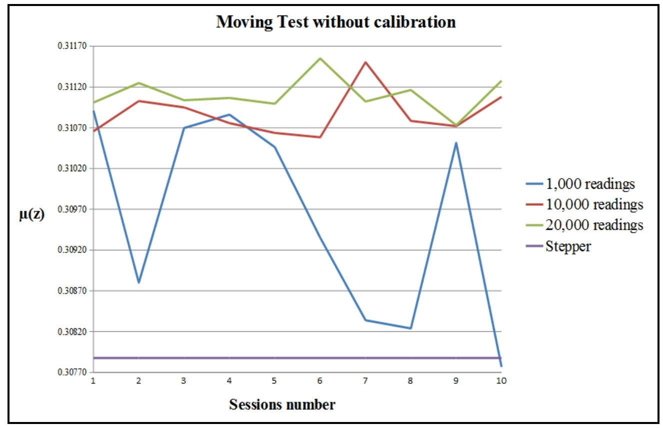

Figure 5. Gyroscope's average angular velocity for 1,000, 10,000 and 20,000 readings compared to the reference angular velocity of the Stepper Motor without calibration

Increasing the number of readings, the red and green line show a more regular trend compared to the blue line, even if they are more shifted upwards than the last one.

The calibration is based on subtracting the Bias error from the average of the number of readings. The following Table IV shows how the averages have changed. Figure 6 highlights how the lines are closer to the reference angular velocity, and this one illustrates and demonstrates the correct algorithm functioning.

TABLE IV. AVERAGE ERROR OF THE GYROSCOPE COMPARED TO ANGULAR VELOCITY OF THE STEPPER WHILE THE DEVICE IS UNDERGOING A ROTATION AND WITH CALIBRATION

Session	**Moving Test with calibration**			
	Test 1 (1,000 r) μ(z)	***Test 2 (10,000 r) μ(z)***	***Test 3 (20,000 r) μ(z)***	***Stepper μ(z)***
1	0.30778804	0.30753398	0.307887	0.30787608
2	0.30567765	0.30790535	0.30812633	0.30787608
3	0.3075752	0.30782735	0.30791503	0.30787608
4	0.30773896	0.30763417	0.30794325	0.30787608
5	0.3073399	0.3075145	0.30787203	0.30787608
6	0.3062301	0.3074606	0.3084285	0.30787608
7	0.3052173	0.30838194	0.30789912	0.30787608
8	0.3051167	0.3076613	0.30804104	0.30787608
9	0.30739218	0.3075977	0.3076086	0.30787608
10	0.30464426	0.3079569	03081546	0.30787608

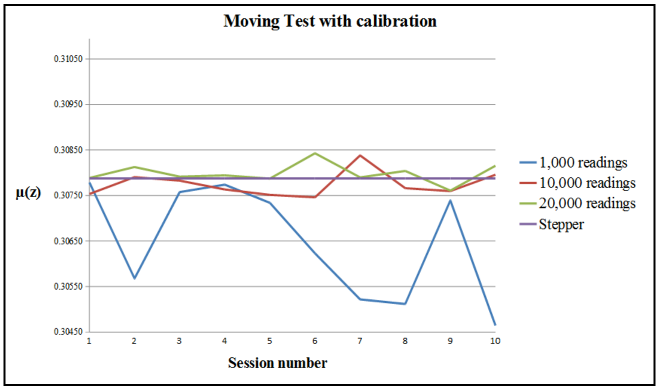

Figure 6. Gyroscope's average angular velocity for 1,000, 10,000 and 20,000 readings compared to the reference angular velocity of the Stepper Motor with calibration

The calibration algorithm has been applied for improving the prototype's functionality of a pedestrian navigation system described in Section III; in this case, is enough to activate the calibration just once at the application's start.

VI. GYROSCOPE VS. COMPASS

Some other tests have been carried out in order to understand if the compass and the gyroscope’s error are affected by larger errors in relation to longer paths and if it is possible to find a breakpoint, at which the two errors are comparable. Figure 7 shows the paths inside the building along six different blocks not subjected to electromagnetic pollution, otherwise the compass's output would be been negatively affected.

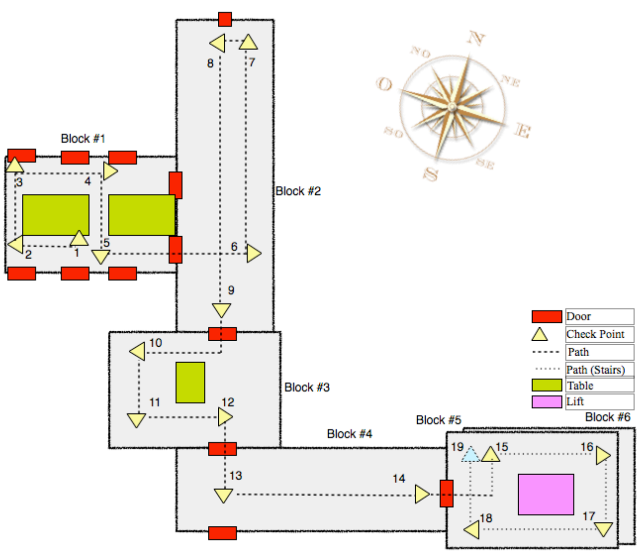

Figure 7. Paths inside a real indoor environment along six different blocks. Each yellow triangle represents a CheckPoint with a predefined orientation

In each checkpoint (described by a numerated triangle), we read the angle rotation of the compass and the gyroscope.

We made 5 paths of different length, starting with the shortest path made of 5 points, and finishing with the longest one made of 19 points, as shown in Table V. The objective is to analyze the absolute error of each sensor as subtracting between the acquired and attempted value. About the gyroscope, the attempted value is a rotation angle composed by a multiple of 90 degrees, while the angle provided by the compass is acquired compared to the real reference system (magnetic north).

TABLE V. REFERENCE PATHS

#Path	*Block1*	*Block2*	*Block3*	*Block4*	*Block5*	*Block6*
1	X					
2	X	X				
3	X	X	X	X		
4	X	X	X	X	X	X

The experimental results have shown how, compared to the gyroscope's absolute error, the compass's absolute error is random and independent from the length of the path, as shown in Figure 8, for a path of 19 checkpoints.

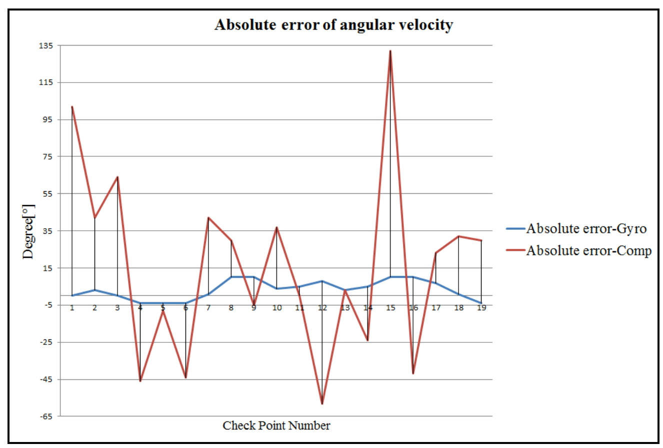

Figure 8. Comparison between the absolute error of Gyroscope and Compass for an indoor path made of 19 CheckPoints

The gyroscope accumulates some errors for rotations in the same verse, while the error decreases for rotation in the opposite verse, resulting in a very small error lying between -4 and 10 degree. The compass’s absolute error instead lies between -58 and 132 degrees.

VII. CONCLUSION

The main objective of this paper was to examine the accuracy level that can be achieved in indoor navigation, specifically for the developed prototype [10][11], using exclusively the gyroscope sensor for the orientation. In order to reach the objective, the output from the gyroscope sensor has been analyzed with the device in static position and throughout a rotation. In both cases, the calibration algorithm satisfies the requirement and ensures a better orientation of the used device in indoor environment. Besides, we have compared the behavior of compass and gyroscope over time and for different paths.

In conclusion, we have established how the gyroscope sensor is better than the compass for indoor navigation, specifically for our mobile application, and how is possible to correct the error introduced from the gyroscope in static position and undergoing rotation.

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