Evaluation of Gyroscope-embedded Mobile Phones

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***Abstract*—Many mobile phone applications such as pedometers and navigation systems rely on orientation sensors that most smartphones are now equipped with. Unfortunately, these sensors rely on measured accelerometer and magnetic field data to determine the orientation. Thus, accelerations upon the phone which arise from everyday use alter orientation information. Similarly, external magnetic interferences from indoor/urban settings affect the heading calculation, resulting in inaccurate directional information. The inability to determine the orientation during everyday use inhibits many potential mobile applications development.**

In this work, we exploit the newly built-in gyroscope in the Nexus S smartphone to address the interference problems associated with the orientation sensor. We first perform drift error analysis and apply this to gyroscope calculations. We test simple as well as complex rotations seen in walking applications. We lastly test the gyroscope's resistance to described interferences. Experiments show angular calculations with percent error no larger than 6% from actual rotated values. Further, we are able to determine the phone's orientation at any time, in magnetically-interfered areas, with the phone accelerating. With this accurate information we can virtually orient the phone to better use mobile-acquired data. This shows that the presence of a gyroscope in smartphones will certainly aid in numerous applications.

***Index Terms*—Mobile phone, Orientation sensor, Gyroscope, Accelerometer, Angular rotation**

I. Introduction

The current rise in mobile technology is leading to a dramatic increase in mobile phone applications. The addition of accelerometers and magnetic field sensors has significantly increased our abilities for data acquisition with these mobile phones. These sensors have led to numerous applications such as activity and gesture recognition, pedometer, and navigation.

However, due to the overtly mobile nature of these devices, using the data effectively is surprisingly tricky business: both the three axis magnetic field sensors and accelerometers are susceptible to the motion and rotation of the mobile device. The orientation of a mobile phone changes constantly during everyday usage like lifting the phone to the ear to listen or putting the phone in the pocket.

Traditional orientation sensors on mobile phones are a combination of accelerometer and magnetic field sensor data. With external interferences such as magnetic fields created by current carrying wires in the walls or accelerations like user walking/running, the orientation sensor cannot accurately determine the orientation of the phone. This severe limitation inhibits many current mobile applications development. For instance, to develop an indoor pedestrian navigation system (i.e. without the use of GPS technology), the phone is often in the user's pocket. But the constant motion of the phone and external magnetic field interferences make it a arduous task to accurately determine the phone's orientation. Similar mobile applications cannot be used in real-life situations without knowing the device's orientation to virtually orient it.

The two principle problems we face are, 1) the varying orientation of the device when placed in user pockets, handbags or held in different positions, and 2) existence of user acceleration and external magnetic fields. A potential solution to these problems could be the use of gyroscopes, which are devices that can detect orientation change. These sensors are known to be immune to external accelerations and magnetic interferences. MEMS based gyroscopes have already found their way in handhelds, tablets, digital cameras to name a few. Interesting applications using a prototype version of a mobile phone with a built-in gyroscope are being developed [1].

The recent introduction of a 3-axis gyroscope in the Nexus S smartphone from Google and Samsung, has motivated us to exploit the ability of this built-in sensor to *calculate the orientation of the device during arbitrary motion*. We develop a general framework that will allow usage of mobile data effectively, especially for mobile application development of different kinds. We hereby formally define the problem statement as: *Can we effectively use the gyroscope technology in the latest smartphones to compensate for accelerative and external magnetic interferences?* We first determine any drift errors caused by integrating gyroscope data, and then test the accuracy of the gyroscope in determining changes in orientation. Finally, we use the gyroscope to address simple navigational needs and, more generally, to determine the mobile phone's orientation in walking tests designed to mimic everyday use. In summary, our contributions are as follows:

- Demonstrating drift error problems that may arise from using the gyroscope, as well as how to correct this error.
- Determination of orientation angles in situations where external magnetic fields and user accelerations are present.
- A general framework for determining mobile phone orientation intended for application developers use in effective mobile data collection.
- Providing a performance analysis of the built-in gyroscope by designing repeatable tests that can validate the characteristics of the gyroscope.

In this paper, Section II provides a brief explanation of the sensors used and the definitions of coordinate frames which the phone operates under. Section III describes the different tests that were undertaken to assess the gyroscope. Section IV, discusses the rotational mathematics necessary to perform vector rotation of inputted measurements. It also provides analysis on the how the orientation of the phone is

TABLE I
BUILT-IN SENSORS

Sensor	Model	Manufacturer	Sensing Axes	Quantity Measured	Range	Vendor
Accelerometer	KR3DM	STMicroelectronics	X,Y,Z	Acceleration	±2g/±4g/±8g	Samsung
	BMA150	Bosch	X,Y,Z	Acceleration	±2g/±4g/±8g	Motorola, HTC, Apple
Magnetic field Sensor	AK8973	Asahi-Kasei	X,Y,Z	Magnetic Field	± 2000μT	Motorola, HTC, Samsung, Apple
Gyroscope	K3G	STMicroelectronics	Y,P,R	Angular velocity	250/500/2000dps	Samsung, Apple (iPhone 4)

calculated and the implications of these calculations. Section V presents the results of gyroscope tests and its usage in solving the problem defined, followed by a brief discussion on the existing work in literature in Section VI. Finally Section VII presents the conclusions of this work and some future work.

II. System Description

In this section, we first define the system used for all data acquisition and the approach for our analysis including the sensors, reference axes, and data collection software.

A. Mobile phone and its sensors

Many smartphones today consists of built-in accelerometers and orientation/magnetic field sensors manufactured using the MEMS technology. But not all of them have a gyroscope. Table I, provides information about various built-in sensors being used in different smartphones. However, we use only the Nexus S in this work due to the inclusion of the gyroscope and most importantly, the ease of the Android programming interface provided by Google. A brief description of the Nexus S built-in sensors is as follows:

1) The KR3DM measures accelerations with respect to the phone. For instance, when the mobile is lying on a table under Earth's gravity, $g = 9.8(-\hat{z})m/s^2$, an acceleration of 9.8 in the +z direction is measured. This is because–as dictated by Newton's third law–the table is actually accelerating the phone upwards. When the phone is dropped into free fall, the z-axis acceleration is equal to zero.
2) The three axis magnetic field sensor is also used as an orientation sensor providing the phone's angular orientations. The orientation sensor outputs three angles in degrees–*yaw, pitch and roll* (we define these shortly), that are calculated from the accelerometer and magnetic field sensor data, which explains the current difficulties in determining the phone's orientation with this sensor.
3) The K3G gyroscope outputs the phone's angular rotational velocity in units of radians/second. Important to note is that the gyroscope measures *changes* in angular orientation.

We stress that the results outlined in this paper are not only applicable in Nexus S. As shown in Table I, Apple's mobile phones also have accelerometers and magnetic field sensors, while the iPhone 4 is further equipped with a 3-axis gyroscope. With the presence of these sensors on other platforms, our framework is not limited to the Android-based mobiles we used for our work. Similarly, as more mobiles continue to become better equipped—especially with the newer gyroscope technology—our results will be applicable to these platforms as well.

B. Application Software

Application software called Blackbox was written in Java, to activate each of the sensors using their respective application programming interfaces (APIs) provided by the Android operating system [2]. The sampling rates for the accelerometer and orientation sensor were chosen to be 8 Hz and the gyroscope as 100 Hz.

C. Coordinate Axes and Reference Frames

All mobile devices lie in the general Cartesian world; hence we chose this space as our working area. However, for the purpose of mobile navigation, we cannot define a fixed initial reference frame. It is natural to define the x, y, and z axes with respect to the mobile device: lying the phone flat and face up on a table, we choose the +x direction to extend out the right edge of the phone, the +y direction to extend out the top edge of the phone, and the +z direction to extend out the front face of the phone.

Fig. 1. Definition of coordinate axes for Nexus S mobile phone

For the orientation angles, we utilize the commonly used *yaw-pitch-roll* (Y,P,R) convention. Each of these angles corresponds to a rotation about one of the principle axes of the phone. The yaw angle, denoted as α, is a rotation about the phone's z axis and is also commonly referred to as the azimuth or heading angle of the phone. The pitch angle, β, is a rotation about the x axis and is changed by tilting the phone upwards or downwards. The roll angle, γ, is a rotation about the y axis of the phone and can be changed by rolling the phone onto its side. By knowing each of these three angles, we can determine the exact orientation of the phone through the proper rotation. The angles are measured from $0°$ azimuth, $0°$ pitch, and $0°$ roll. To obtain the current orientation of the phone, standard rotational mathematics can be performed to first rotate the phone through azimuth α, then through pitch β, and finally through roll γ. The sequence of rotations must be in this order. Finally, our initial work with the orientation sensor led us to define the positive orientation direction to be consistent with the AK8973 output: $+\alpha$ denotes a clockwise yaw rotation, $+\beta$ denotes a downwards pitch rotation, and $+\gamma$ denotes a counterclockwise roll rotation.

III. Methodology

We collected data using the built-in sensors described in Section II. To test the accuracy and use of angular calculations of rotations, we performed drift, rotation, and application tests. We briefly explain these tests and present the results in Section V.

1) Drift Tests: As with any calculation involving integration of data, there tends to be accumulation of small drift errors over time, especially as the number of data points is increased. Figure 2 shows that the output data values from the gyroscope are never exactly zero–even if the phone is completely stationary. When these small values are integrated, they will artificially increase (or decrease) our final integrated result. Further, in order to understand factors such as variation of the drift from one test to another and dependence of drift on the orientation of the phone, we conducted 15 drift tests.

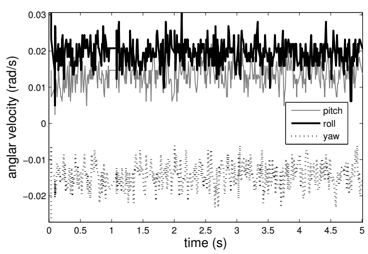


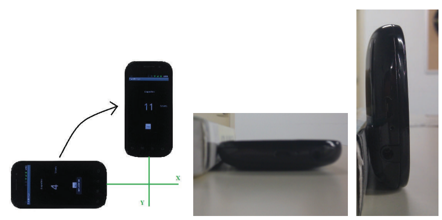
Fig. 2. Even when lying completely stationary, raw values of the gyroscope give roughly $\pm$0.01-0.03 radians per second of angular velocity—a small value that we must correct for.

For every trial, the phone was laid completely stationary during the entire test. If there was no drift in the sensor, integrated angular changes should theoretically be $0°$. Values larger than this suggest existence of drift that must be compensated for. We also put the phone in arbitrary orientations to determine if these placements had any effect. In other words, for some tests it was flat on a surface, for others it was set vertically against a wall, or placed randomly on an uneven surface. Figure 3 depicts a sample placement of the phone for these tests.

2) Rotation Tests: To verify simple angular calculations, we performed basic rotations such as a $90°$ yaw rotation, a $-90°$ pitch rotation, or a combination of two rotations. We started the data collection with the phone at some initial orientation and then rotated to a desired angle. The data from each axis was then integrated and adjusted to compensate for calculated drift errors. For each of the 8 rotations presented, we performed the test 10 times and averaged each axis' tests together. The final angles were then compared to the known rotation (determined by the phones actual position against the rigid surfaces). Figure 4 depicts the rotation of the phone and also the placement of the phone for the pitch and roll calculations.

(a) (b)

Fig. 3. Drift test (a) Here the phone is placed on a flat surface (b) Here the phone is rested nearly vertically on a soft couch.



(a) (b) (c)

Fig. 4. Rotation tests. (a) Shows a simple $90°$ yaw rotation performed. A -$90°$ roll rotation is shown from (b) to (c)

3) Application Tests: In this paper, we consider the arbitrary nature of human walking patterns as a challenge to our angular calculations from the gyroscope. As such, it was necessary to develop a repeatable test to collect walking data with the mobile phone. We consider the case where the user puts the mobile phone is his/her pocket and walks about accordingly. Clearly, the orientation will change randomly, dependent upon the users gait, looseness of clothing, and depth of pocket or bag. In each test the phone was placed on the ground for a period of 5-10 seconds. This was done to ensure the drift corrections were adequate, so that the accumulating angles remained zero during this time. Then the phone was placed in the users pocket and the walking commenced. Tests of this nature included walking straight, turning, and riding in an elevator. At the end of the test, the phone was placed back onto the ground for 5-10 seconds followed by the termination of the data collection. Similar tests were conducted with the mobile in a woman's purse, in a backpack, and held to the user's ear to simulate motion during a conversation.

IV. Mathematical discussion

The main problem defined is the orientation sensor's susceptibility to external interference—thus inhibiting true orientation determination using this sensor. In this section, we offer mathematical proof of the sensor's inadequacies by showing dependence on external fields. We also discuss the pertinent mathematics of the gyroscope: the solution to the problem.

A. *Calculation of Azimuth, Pitch, and Roll angles*

Pitch and roll calculations are calculated from the accelerometer data. This is accomplished by determining the accelerometer's deviation from Earth's downward gravitational field. Pitch can be found by computing the arctangent of the ratio of a_y to a_z. Hence,

$$\beta = -tan^{-1}(a_y/a_z) \tag{1}$$

The negative sign results from the fact that the AK8973 sensor regards an upward pitch as a negative pitch angle. A similar procedure can be performed for roll rotation given as,

$$\gamma = -tan^{-1}(a_x/a_z) \tag{2}$$

The azimuth angle is synonymous with the compass heading which the phone faces, and it outputs an angle in the range of $[0, 360)°$. It can be computed by taking the x and y components of Earth's magnetic field with respect to the phone and comparing this to the x and y components of the Earth's magnetic field that naturally points to magnetic North. However, we must first ensure that the phone measurements are oriented to the x-y plane, i.e, β=γ=0°. Then, we can find the angle between this vector and Earth's magnetic vector, $\vec{E}$. Thus taking a measured magnetic field vector, B_x B_y and B_z, equation 3 can be used to rotate this vector to the horizontal plane given the phone's pitch and roll angles from equations 1 and 2.

$$\begin{pmatrix} B_x\prime \\ B_y\prime \\ B_z\prime \end{pmatrix} = \begin{pmatrix} \cos(-\gamma) & 0 & \sin(-\gamma) \\ 0 & 1 & 0 \\ -\sin(-\gamma) & 0 & \cos(-\gamma) \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(-\beta) & -\sin(-\beta) \\ 0 & \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} \tag{3}$$

Then

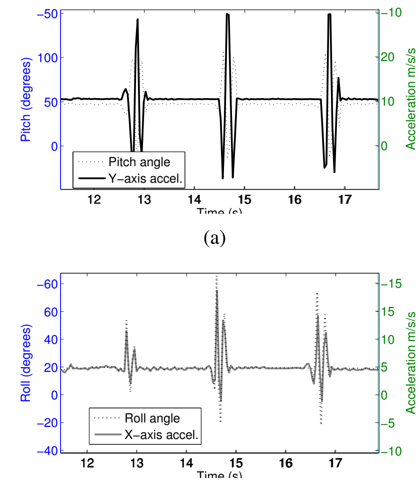
$$\alpha = \cos^{-1}\left(\frac{\vec{B'} \cdot \vec{E}}{|\vec{B'}| \cdot |\vec{E}|}\right) - \delta_e \tag{4}$$

The last term, δ_e, is the easterly magnetic declination. Earth's magnetic field does not point to true North and is off by an angular amount known as magnetic declination. We used NOAA geomagnetic data [3] to calculate this declination at our location (33.254121°N, 97.141799°W), which was 4° 17' east declination.

B. *Effects of Acceleration on Orientation Angles*

The fact that pitch and roll angles are calculated directly from accelerometer data complicates matters considerably. The sensor cannot identify whether or not changes in acceleration values are a result of actual accelerations, or merely changes in the orientation of the phone. Thus, all orientation angle calculations using accelerometers are only valid for a stationary mobile device. Any acceleration of the phone will change the measured acceleration, and thus affect the pitch and roll calculations. Without proper pitch and roll angles, we cannot orient the phone to the XY plane as required for the azimuth calculation. All angles are distorted.

To demonstrate the effect of external accelerations on the pitch and roll output, we designed a simple "jerk" test. The mobile was placed flat on a table, such that β=γ=0°. We then jerked the phone severely along the y-axis, stopped it, and then jerked the phone again a few seconds later. We repeated this process with jerks in the x direction. Of particular importance is that the phone remained completely flat against the table throughout the test. The results are depicted in Figure 5. From



(a)

(b)

Fig. 5. Jerk test (b) A y axis acceleration of 2g caused the phone to output a $40-60°$ pitch change) (a)Likewise, an x axis acceleration of 1g caused the phone to output a $25-35°$ roll change).

Figure 5 we can see that there is not only a direct correlation between acceleration and perceived orientation but also the amount by which the pitch and roll angles are distorted is impressive—even though the phone remained completely flat during the test. This shows that the AK8973 orientation sensor performs pitch and roll calculations based on the accelerometer input. Without an acceleration-independent sensor (i.e. gyroscope), it is not possible to determine arbitrary accelerations exerted on the mobile device. Since both pitch-and-roll and accelerometer values are dependent upon each other, there is no way to resolve either one (except of course, the specific trivial case when a_x=a_z=0).

C. *Calculation of Angles using Gyroscope*

The gyroscope gives angular velocity output in radians/second. Let ω_α, ω_β, ω_γ be the angular velocities of the yaw, pitch, and roll orientation angles. Since each orientation angle is independent, we can determine the angles with simple integration:

$$angle_i = \int_{t_0}^{t_f} \omega_i \, \mathrm{d}t, \quad i = \alpha, \beta, \gamma \tag{5}$$

This equation is ideal for continuous data; since the sampling intervals for the sensors in the phone are discrete, we treat this integral as its equivalent summation. In addition, there exists an accumulative drift error in each of the axes, which we must compensate for. Thus, the final calculation for each orientation angle is:

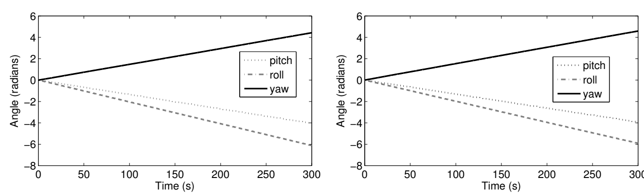
$$angle_i = \sum_{0}^{t} [-\omega_i \mathrm{d}t] + \delta_i, \quad i = \alpha, \beta, \gamma \tag{6}$$

where ω_i is the raw value obtained from the gyroscope, $\mathrm{d}t$ is the time differential corresponding to the gyroscope measurement, *t* represents the total time of the test, and δ_i is the angular drift correction. The negative sign arises because the gyroscope's positive measurements indicate negative angular changes by our axial definition. The drift correction determination and the accuracy of these calculations is discussed in Section V.

V. Results

A. Drift Tests

Collecting the data from the drift tests, we integrated the raw data and the integrated angles were plotted against time as depicted in Figure 6.



(a) (b)

Fig. 6. In both (a) and (b), the integrated angles for the two independent tests show very similar linear drift.

We can see each test produced similar slopes for each axis. Regardless of the orientation of the phone, the consistency of the slopes suggests that the total drift can be predicted and compensated for. Over 15 tests, the average drift for the pitch, roll, and yaw axes were -0.013314 rad/s, -.020387 rad/s, +.015795 rad/s respectively.

Since the gyroscope's output values are the opposite of the actual change, it is important to note that negative slopes actually indicate a positive angular drift, and positive slopes indicate a negative drift. Due to linearity and consistency of the drift, we can account for this via δp = +.013314t, δr = +.020387t, and δy = -.015795t where δp, δr and δy are the average angular pitch, roll, and yaw drift corrections in radians for 15 tests and t is the time in seconds (we must add to negative drifts and subtract from positive drifts to compensate). *Note:* In all data beyond this point, we have taken our raw integrated values and added the corresponding drift compensation based on these tests.

To conclude, we can say that integrating the gyroscope data obtained from the drift tests produces a predictable and linear drift that can be compensated as explained above.

B. Rotation Tests

To demonstrate the gyroscope's ability to sense rotations, we first show a figure depicting a test where we rotated the phone 90° yaw followed by a -90° roll rotation. Note that each axis is clearly independent of each other; for instance, the yaw rotation had no effect on the roll and pitch angle.

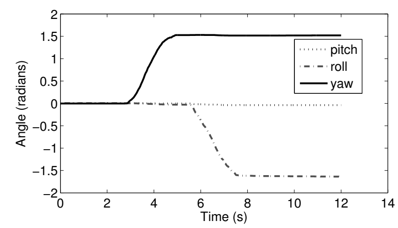


Fig. 7. Integrated orientation angles from gyroscope data shows a simple 90° yaw followed by a -90° roll rotation.

Also, the actual pitch angle was not rotated at all and thus the calculated pitch angle remained unchanged throughout the test. We performed 8 rotations to obtain the accuracy of the integration process. Table II shows the results of this test. Each test is indicated in the [yaw,pitch,roll] format. Thus, the test indicated with [0,-90,0] shows the results when we rotated the phone with -90° pitch.

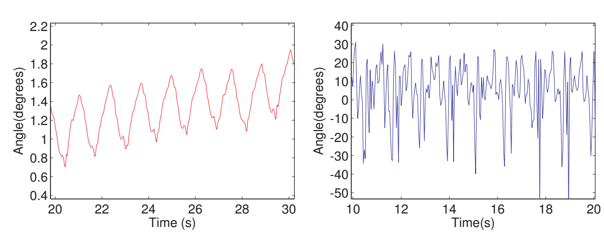
TABLE II
Rotation Tests

Actual Rotations	Calculated Rotations			Percent Error		
Yaw,Pitch,Roll	Yaw	Pitch	Roll	Yaw	Pitch	Roll
[90,0,0]	89.2	-0.4	-3.4	0.9	0.5	3.7
[180,0,0]	178.7	-0.3	-5.4	0.7	0.2	3.0
[0,-90,0]	0.1	-94.6	-2.7	0.1	5.1	3.0
[0,0,-90]	0.0	0.5	-92.8	0.0	0.5	3.1
[90,0,0] & [-90,0,0]	0.4	0.4	0.4	0.4	0.5	0.2
[90,0,0] & [0,0,-90]	84.7	-1.8	5.3	5.9	2.0	2.6
[-90,0,0] & [0,-90,0]	-88.7	-94.8	-3.3	1.4	5.4	3.6

From the table, it can be inferred that integrating the gyroscope produces very accurate results. In all cases, the angle was predicted to within 6%. Even in sequential rotations, the angle was calculated with good accuracy. Further, there was very little error in the axes that were not the principle axes of rotation.

C. Application Tests

As explained in Section IV, the phone was placed in the pocket of the user's trouser, who then walked in a straight line. This caused changes in the orientation of the phone due to the motion of the phone within the users pocket. Figure 8 shows the roll data from the gyroscope and the orientation sensor for one such test. It is also clear that the noticeable interferences present in the compass data are not present in the angular integrations obtained from the gyroscope.



(a) (b)

Fig. 8. (a) The roll angle calculated from the gyroscope data is smooth and largely sinusoidal (b) The roll angle obtained from the orientation sensor shows an irregularity, caused by the acceleration of the user's walking.

Further, we are able to detect turns in the users motion–even if the phone was in the pocket. This has clear navigational application. Notice in Figure 9 that each turn can be clearly identified by the sharp change in one of the axis.

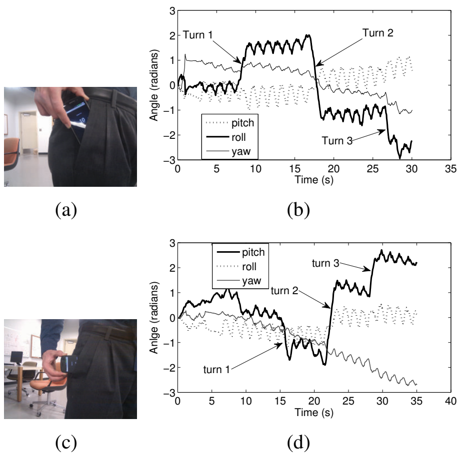


Fig. 9. (a) Lengthwise placement of the phone inside the pocket yielded results seen in (b) Note the turn indication in the roll axis. (c) Horizontal placement of the phone inside the pocket yielded results seen in (d) Note the turns are still detected, this time in the pitch axis.

Although the azimuth angle is changing, we notice a change in the roll of the phone. This is due to the way the phone is oriented within the pocket (lengthwise) as depicted in Figure 9(a). If the phone rests in the pocket sideways as in Figure 9(c), we can still determine if the user turns by noticing the change in the pitch of the phone. Note that we have plotted all three orientation angles as a function of time, thus determining the orientation of the phone at any time. The turns are clearly seen regardless of the orientation of the phone within the user's pocket.

Very similar results were obtained in three other related tests. Figure 10 shows the calculated orientation for the three more walking scenarios: the mobile in a user's backpack, at the ear during a conversation, and in a woman's purse.

In each test, angular calculations are smooth, sinusoidal, and continuous. This data, in conjunction with other sensors, can be used to effectively address many navigational needs for walking users.

Finally, in Figure 11 we present the issue of magnetic interference. We compare the azimuth angle data collected from the orientation sensor with the change in azimuth angle measured by the gyroscope. In this test, the user held the mobile and walked straight (i.e. no change in azimuth) but through a magnetically-interfered area consisting of ferromagnetic pillars along the hallway. While the orientation sensor is deflected considerably, the gyroscope accurately shows no change in azimuth angle.

D. Elevator Test – Culmination of Results

The results of the elevator test were promising. The test is similar to the walking tests, except the user walked down a hallway, into an elevator, traveled down in the elevator, then back up in the elevator, and finally walked back out down the hallway. The test included turns, indoor magnetic

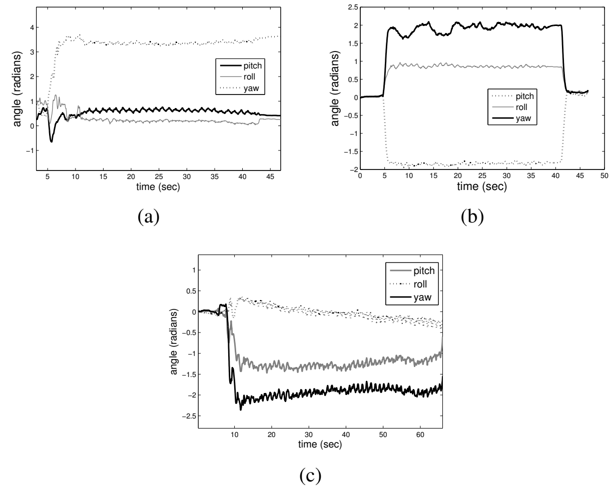


Fig. 10. The orientation angles calculated in walking scenarios when phone is: (a) in a backpack, (b) at the user's ear during conversation, and (c) in a woman's purse.

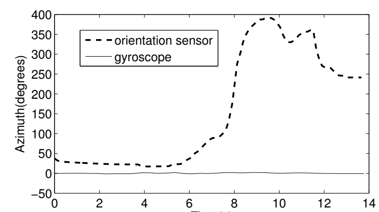


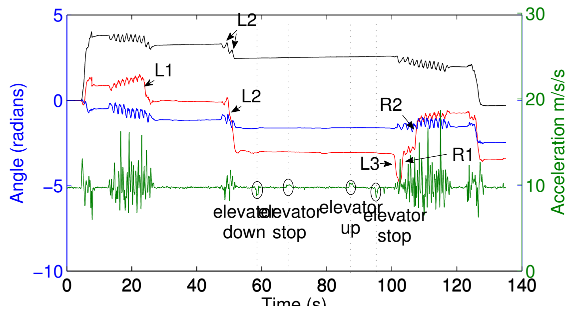
Fig. 11. Magnetic interference is clearly present in the orientation sensor which causes sudden increase in azimuth measurement, whereas the gyroscope calculation correctly dictates no change in orientation. Note that the orientation sensor measures *actual* orientation while the gyroscope measures *changes* in orientation.

interferences, and accelerations both laterally and vertically. Figure 12 depicts the data collected from the accelerometer and the gyroscope.

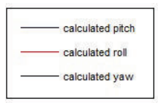
We highlight the important results. First, the device's orientation angles are able to be determined at any time t. Yet unlike the orientation sensor these are not affected by external accelerations, which is demonstrated by the aligned data at the times marked by vertical dashed lines. Here, the user was standing stationary in the elevator as it moved up and down. Even in the presence of accelerations, the gyroscope angular calculations correctly showed no change in orientation. Further, left and right turns are detected and distinguishable. In short, this plot shows the phone's orientation at all times, regardless of the situation or interferences upon the phone.

VI. Related Work

Schall et al [3] combine a visual tracking equipment and built-in sensors of a smartphone to estimate relative rotations of the device. Kunze et al [4] infer the orientation of mobile device carried in a pocket from the acceleration signal acquired when the user is walking. However this work pertains to outdoor experiments and hence does not account for the magnetic interferences indoors. Blanke [5] work with sensors placed freely in a trouser pocket by using sequences



(a)



(b)

Fig. 12. Elevator test data: The acceleration interferences are not seen in the gyroscope data and the turns are clearly visible (and are even distinguishable between left and right turns). Note that all orientation angles are measured as a function of time.

of the user's headings, extracted with PCA on Gyroscope measurements projected to a global frame, to learn and recognize predefined transitions indoors. Steinhoff [6] present results of dead reckoning considering placement of a mobile device in different kinds of pockets. Ladetto et al [7] develop a wearable dead reckoning unit consisting of a gyroscope, compass, and accelerometer, but they only use the gyroscope for correcting the compass heading errors due to magnetic interferences. Moreover their unit has to be fixed to the hip, thereby constraining the orientation of the unit. In a later work by Ladetto et al [8] a gyroscope is used to assist in navigation, but is not the primary method of orientation calculation–it merely serves as a backup to correct magnetic interferences. Sun [9] perform activity recognition using a mobile phone's built-in accelerometer. However they do not consider the cases where the mobile may slip or rotate when the user is moving but only consider certain predefined positions of the mobile phone in a pocket. Kai [10]. Jiangpeng et al [11] utilizes sensors for drunk driving detection, but notes that sliding of the phone (i.e. orientation change) had "obvious impacts" on detection accuracy.

In contrast, our work uses the gyroscope as the primary determinant of orientation. Our evaluation resolves many of the limitations experienced in other works, namely the unaccounted accelerations and magnetic interferences. Finally, we determine the orientation in general cases, without any constraints on the system.

VII. Conclusion and Future Work

Orientation sensors are ineffective in determining orientations due to the magnetic and accelerative interferences resulting from general use. By integrating the angular velocity output of the Nexus S gyroscope, we were able to predict angular orientations to within 6% for test rotations, as well as detecting turns while the phone's orientation was constantly changing. When the user was walking, taking turns, and traveling up and down an elevator, the orientation of the phone was able to be determined. All of these results are improvements upon–and our proposed replacement to–the data collected by the orientation sensor that is so easily interfered with by external fields.

By knowing the orientation of the phone at any time, it is possible to perform standard rotational mathematics to rotate measured vectors to a desired reference frame. In a general sense, any additional data that the mobile can potentially collect can be meaningfully analyzed by knowing the phone's correct orientation at all times. The effective use of this data can transform our mobiles into much stronger machines.

As part of future work, we aim to utilize the gyroscope's ability in solving the problems mentioned above by developing a sensor fusion based indoor tracking application that combines the sensor data from the gyroscope, accelerometer and the orientation sensor.

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