



A Thesis

On The Topic

**Understanding the Effect of Positioning on Mobile
Sensor Data and Its Impact on Applications**

Presented In Partial Fulfillment Of The Requirements For The Degree Of

Master Of Technology
In
Computer Science & Engineering

By

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Certificate

This is to certify that Garvita Saxena, has completed the thesis entitled "**Understanding the Effect of Positioning on Mobile Sensor Data and Its Impact on Applications**" and submitted it in partial fulfillment of the requirements for the degree of Master in Technology at the Indraprastha Institute of Information Technology, Delhi. This is an original work done under my guidance and supervision.



Prof. Pushpendra Singh

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Abstract

Most sensor based mobile phone applications like navigation systems, pothole detection, pedometers, traffic detection, etc. rely on the strict and stable positioning of the mobile phone at a particular place throughout their usage. Most of these applications also use accelerometer and orientation sensor data which is highly sensitive and susceptible to the external magnetic interferences, resulting in inaccurate information about the directions. Our aim is to study the usage of modern sensors like gyroscope and rotation vector sensor to improvise the ability of smartphones to track movement. And also, to reduce the effort of stable positioning of the phones by virtually reorienting it along the three axes. This will also address the interference problems associated with the orientation sensor. This is necessary because the data that we get from the sensors is with respect to the orientation of the phone, i.e., along its own x, y and z axes. But we would first rotate the phone virtually from its own axes to the actual axes by applying rotational mathematics. This would help many applications which use sensor data to become independent of the phone's position. We evaluate our results by comparing the original values and the calculated values of the sensor by calculating the correlation coefficient. We get the best results for the rotation vector sensor and conclude that it is the most reliable sensor which can be used to virtually reorient a smartphone.

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Understanding the Effect of Positioning on Mobile Sensor Data and Its Impact on Applications

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1 Introduction

There has been an incredible growth in mobile computing capabilities and sensing technologies in the past few years. We can take a lot of advantage by the deployment of many sensor based mobile phone applications like navigation systems, pothole detection, pedometers, traffic detection, etc. But most of these applications rely on the strict and stable positioning of the mobile phone at a particular place throughout their usage.

Accelerometer and orientation sensor data are also used by these applications. It is not easy to use this data in an effective manner as the accelerometers and the three axis magnetic field sensors are very prone to the rotation and motion of the mobile device [1], because of the highly mobile nature of the devices. The phone is mostly in constant motion in majority of the sensor based applications as mentioned above. But it becomes difficult to assess the phone's orientation accurately, mainly because of the presence of external magnetic field interventions and the constant motion of the phone almost all of the time. Thus, without knowing and understanding the device's orientation to virtually reorient it, similar applications cannot be used in real-life scenarios.

Our aim is to study the usage of modern sensors like gyroscope and rotation vector sensor to improvise the ability of smartphones to track movement and to reduce the effort of stable positioning of the phones by virtually re-orienting it along the three axes. This will also address the interference problems associated with the orientation sensor. This is necessary because the data that we get from the sensors is with respect to the orientation of the phone, i.e., along its own x, y and z axes. But we would first rotate the phone virtually from its own axes to the actual axes by applying rotational mathematics. This would help many applications which use sensor data to become independent of the phone's position.

We perform drift test on the gyroscope sensor and the rotation vector sensor and apply the drift correction in their rotation calculation. We also carry out tests which proved that by integrating the angular velocity output of the gyroscope, we can predict the angular orientations very accurately for test rotations. The same test was also carried out by using the rotation vector sensor and it showed even better results. We also show that gyroscope and rotation vector sensors have much better orientation and movement detection capabilities than the orientation sensor.

We evaluate our results by comparing the original values and the calculated values of the sensor. We do this by calculating the correlation coefficient between the original and changed values. We obtain values of correlation coefficient almost close to 1 in case of the rotation vector sensor and conclude that it is the most reliable sensor which can be used to virtually reorient a smartphone.

2 Related Work

Most mobile sensor based applications rely on the use of the accelerometers and orientation sensors embedded in the smartphone. To address the interference problems associated with the orientation sensor, Barthold et al. [1], used the built-in gyroscope to address the interference problems in a smartphone which was associated with the orientation sensor. Several tests like drift tests, rotation tests, application tests, etc. were done and the results proved that when we integrate the angular velocity output of the gyroscope,

it allows the prediction of angular orientations to less than 6% for test rotations, also it detected the turns while the phone's orientation was constantly being altered.[1]

To analyse road conditions and identify good road segments, Eriksson et al. [3], gather data from the vibration and GPS sensors and process this data by exploiting the inherent mobility of the participating vehicles. They define good road segments as the road segments which encounter potholes less than 0.2% of the time and they were able to build a detector for the same. However, they have fixed the accelerometer of the mobile device on three different positions. The first position was when the mobile phone was attached to the dashboard of the vehicle, the second one was when the mobile phone was attached to the right side of the windshield and the third position was when the mobile phone was attached to the embedded PC. [3]

In order to virtually reorient a mobile sensor, Prashanth Mohan et al. [5], have proposed an algorithm which can virtually reorient a disoriented accelerometer automatically. Their system, called Nericell, only keeps its GSM radio and the accelerometer turned on throughout the usage of the application. Their work is a major improvement and a key distinction from the prior work on Pothole Patrol [3] that leverages a dedicated accelerometer mounted at a known orientation. Sunil Sharma et al. [8] also adopted a similar approach by making use of machine learning algorithms on accelerometer data to detect potholes and then perform classification of roads based on the same.

To address the issue of obtaining accurate orientation information from mobile sensors, Valentina Marotto et al. [4] focussed on this problem in a similar way. They investigated the gyroscope use as the primary determinant of orientation. They did many tests depicting how the proposed way can correct the error due to the use of gyroscope. They tested for two positions of the phone. The first one was when the phone was under some rotation and the second one was when the phone was in a static position. They concluded that the gyroscope sensor is capable of providing better orientation information than the magnetic compass. [4]

3 Methodology

3.1 Data Collection

We made an Android application to collect and do the necessary calculations on the data available from different sensors of the phone. We have tested our application for the smartphone RealMe X2.

3.2 Coordinate Axes and Reference Frames

We define the x , y , and z axes with respect to a fixed position of the phone as shown in Figure 1, i.e, when the phone is lying flat on a table with the phone facing up. Now, to the phone's right edge, the $+x$ direction will extend and will correspond to the pitch, to the phone's top edge, the $+y$ direction will extend and will correspond to the roll and finally, to the phone's front face, the $+z$ direction will extend which correspond to the azimuth or the yaw. With respect to the orientation angles, we utilize the YPR convention i.e. Yaw-Pitch-Roll. Every angle corresponds to rotation about the phone's principal axes.

For the orientation angles, we make use of the Yaw-Pitch-Roll (YPR) convention. Each of these angle angles correspond to a rotation about one of the principal axes of the phone. These angles have been defined as follows:

1. Azimuth angle is the degrees of rotation about the phone's z axis. It is denoted by α . We can visualize this angle as follows: If the top edge of the mobile phone faces magnetic north, the azimuth angle will be 0 degrees; if the top edge faces south, the azimuth will be 180 degrees. Likewise, if the top edge faces east, the azimuth will be 90 degrees, and if the top edge faces west, the azimuth will be 270 degrees. It is the angle between the phone's current compass direction and the Earth's magnetic north.
2. Pitch angle is the degrees of rotation about the phone's x axis. It is denoted by β . We can visualize this angle as follows: if we hold the

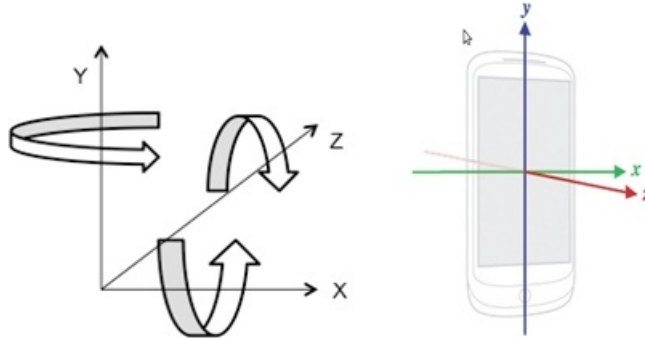


Figure 1: Rotation angles and axes of a smartphone

mobile phone parallel to the ground with the bottom edge towards our side and then tilt the top edge of the device toward the ground, then the pitch angle will become positive. It will be altered if we tilt the phone in an upward or downward direction. If we tilt the phone in the opposite direction, it will cause the pitch angle to become negative. The range of values is from -180 degrees to 180 degrees. It is the angle between a plane parallel to the phone's screen and a plane parallel to the floor.

3. Roll angle is the degrees of rotation about the y axis. It is denoted by γ . We can visualize this angle as follows: if we hold the mobile phone parallel to the ground with the bottom edge towards our side and then tilt the left edge of the phone towards the ground, then the roll angle will become positive. Likewise, if we tilt the phone in the opposite direction, it will cause the roll angle to become negative. The range of values is from -90 degrees to 90 degrees. It is the angle between a plane perpendicular to the phone's screen and a plane perpendicular to the floor.

The exact orientation of the phone can be determined through proper rotation by being aware of the 3 angles. We have studied the following listed sensors:

1. Accelerometer

2. Orientation
3. Gyroscope
4. Rotation Vector

3.3 Accelerometer Sensor

The accelerometer sensor is used to measure the acceleration force exerted on the sensor along all the phone's axes, also taking into account the gravitational force of the Earth. The acceleration force data exerted on the x, y, and z axes is measured in m/s^2 . The accelerometer gives the value of $g = 9.81m/s^2$, because of the presence of the Earth's gravitational force. Similarly, the accelerometer gives the value of $g = 0m/s^2$, when the phone is falling freely at $9.81m/s^2$ while rapidly accelerating towards the ground.

However, we show that due to the highly mobile nature of this sensor, it is extremely susceptible and prone to the motion and rotation of the mobile phone and also to the external magnetic interferences. Hence, it cannot be solely used to determine the orientation of the mobile phone accurately.

3.3.1 Steps Followed:

1. With a sampling rate of 10^9 microseconds, calculate the values a_x , a_y and a_z from the accelerometer sensor.
2. Find the angles α , β and γ . These angles can be calculated by using the given formulas:

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

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

- (c) The azimuth angle, α can be computed by taking the x and y components of the Earth's magnetic field. This angle is similar with the magnetic compass heading in the direction which the

phone faces. Hence, the x and y components of the magnetic field can help in its computation as it naturally points to the magnetic north. But, the phone should be oriented to the x-y plane, i.e., ($\beta=\gamma=0$). To do that, we will rotate the vector to the horizontal plane given β and γ as shown in Eq. 3. M_x , M_y and M_z is the measured magnetic field vector.

$$\begin{bmatrix} M'_x \\ M'_y \\ M'_z \end{bmatrix} = \begin{bmatrix} \cos(-\gamma) & 0 & \sin(-\gamma) \\ 0 & 1 & 0 \\ -\sin(-\gamma) & 0 & \cos(-\gamma) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(-\beta) & -\sin(-\beta) \\ 0 & \sin(-\beta) & \cos(-\beta) \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} \quad (3)$$

- (d) The last term, δ_e in Eq. 4 is the magnetic declination. This value is calculated with the help of Magnetic Field sensor.

$$\alpha = \cos^{-1} \frac{M' \cdot E'}{|M'| \cdot |E'|} - \delta_e \quad (4)$$

3. To obtain the current orientation of the phone, apply rotational mathematics as shown in Eq. 5:
- (a) Rotate the phone through α . (along z axis)
 - (b) Rotate the phone through β . (along y axis)
 - (c) Rotate the phone through γ . (along x axis)

$$\begin{bmatrix} O_x \\ O_y \\ O_z \end{bmatrix} = \begin{bmatrix} \cos(-\alpha) & -\sin(-\alpha) & 0 \\ \sin(-\alpha) & \cos(-\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(-\gamma) & 0 & \sin(-\gamma) \\ 0 & 1 & 0 \\ -\sin(-\gamma) & 0 & \cos(-\gamma) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(-\beta) & -\sin(-\beta) \\ 0 & \sin(-\beta) & \cos(-\beta) \end{bmatrix} \quad (5)$$

3.4 Orientation Sensor

By processing the raw sensor data from the geomagnetic field sensor and the accelerometer sensor, the orientation sensor derives its data. The precision and accuracy of the orientation sensor is diminished to a significant extent, because of the heavy processing which is involved in the sensor.[2]

3.5 Gyroscope Sensor

The gyroscope sensor provides the measurement of the rate of rotation around a device's x, y, and z axis in radians/s. It uses the same sensor coordinate system which is used for the accelerometer sensor. When we look at the mobile phone from any positive point on the x, y, or, z-axis, such that that the mobile phone has been placed on the origin, then a positive rotation is reported if the mobile phone is rotating in the counter-clockwise direction.[2]

3.5.1 Steps Followed:

1. With a sampling rate of 10^9 microseconds, calculate the values g_x , g_y and g_z from the gyroscope sensor.
2. Let the angular velocities of the yaw, pitch, and roll orientation angle be represented as ω_a , ω_b and ω_c respectively. We can determine all the angles with easy integration because no orientation angle is dependent on each other as shown in Eq. 6.

$$angle_i = \int_{t_0}^{t_f} \omega_i dt; i = \alpha, \beta, \gamma \quad (6)$$

3. But the above equation is ideal for continuous data. In our case, since the sensors have discrete sampling intervals, we treat this integral as its equivalent summation. Thus, the final calculation for each of the orientation angle will be as shown below. In our case, we are summing up 10 values at a time to maintain the required granularity of the data. Here, δ_i is the angular drift correction which was obtained by doing the drift test. The negative sign for the angular velocity arise here because by our definition of axes, the positive measurements of the gyroscope indicate negative angular changes.

$$angle_i = \sum_0^t -\omega_i dt + \delta_i; i = \alpha, \beta, \gamma \quad (7)$$

4. Now, we have got the aggregated values of the three angles for discrete time instances. We now apply rotational mathematics as done with the accelerometer.

5. To obtain the current orientation of the phone, refer Equation 5.

3.6 Rotation Vector Sensor

The orientation of the device as a combination of an axis and an angle, in which the phone has rotated through an angle θ around x, y, or z-axis, is represented by the data of the rotation vector sensor.[2] Elements of the rotation vector are unitless. The rotation vector sensor integrates data from the accelerometer sensor, magnetometer sensor and the gyroscope sensor. The three elements of the rotation vector sensor are expressed as follows where the magnitude of the rotation vector is equal to $\sin(\theta/2)$, and the direction of the rotation vector is equal to the direction of the axis of rotation. The three elements of the rotation vector sensor correspond to the last three components of a unit quaternion ($\cos(\theta/2)$, $x * \sin(\theta/2)$, $y * \sin(\theta/2)$, $z * \sin(\theta/2)$).[2]

1. $x * \sin(\theta/2)$
2. $y * \sin(\theta/2)$
3. $z * \sin(\theta/2)$

The x, y, and z axis here are defined in the same way as they are defined in the acceleration and gyroscope sensor. The reference coordinate system is defined as a direct orthonormal basis. Following are the characteristics of this coordinate system:

1. The vector product of Y x Z defines the X. It points approximately towards east and is tangential to the ground at the current location of the phone.
2. Y points towards the geometric North Pole and is also tangential to the ground at the current location of the phone.
3. Z is perpendicular to the ground plane and points towards the sky.

	Position 1	Position 2
g(x)	-1.42E-04	-1.42E-04
g(y)	-0.000126156	-0.000126156
g(z)	-0.000120197	-0.000120197

Table 1: Average Drift Present In Gyroscope Sensor In Two Different Positions

3.6.1 Steps Followed:

1. With a sampling rate of 10^9 microseconds, calculate the values r_x , r_y and r_z from the gyroscope sensor.
2. Obtain the aggregated values of the three angles for discrete time instances as done in the case of gyroscope. Calculate the drift error δ_i . Refer to Eq. 8.

$$angle_i = \sum_0^t -r_i dt + \delta_i; i = \alpha, \beta, \gamma \quad (8)$$

3. Sum up 10 values at a time to obtain the aggregated values of the three angles for discrete time instances. We now apply rotational mathematics as done in the previous cases.
4. To obtain the current orientation of the phone, refer Equation 5.

4 Observations & Results

4.1 Drift Test

Sometimes, even when the phone is stationary, the gyroscope and the rotation vector sensor still shows some values. This accounts for the drift error. The results of the drift test for gyroscope are shown in Table 1 and 2. Figure 2 and Figure 3 are illustrations of the drift observed in two different stationary positions of the phone. From Table 1, we observe that the two plots are quite identical to each other with respect to the range of the values showing the

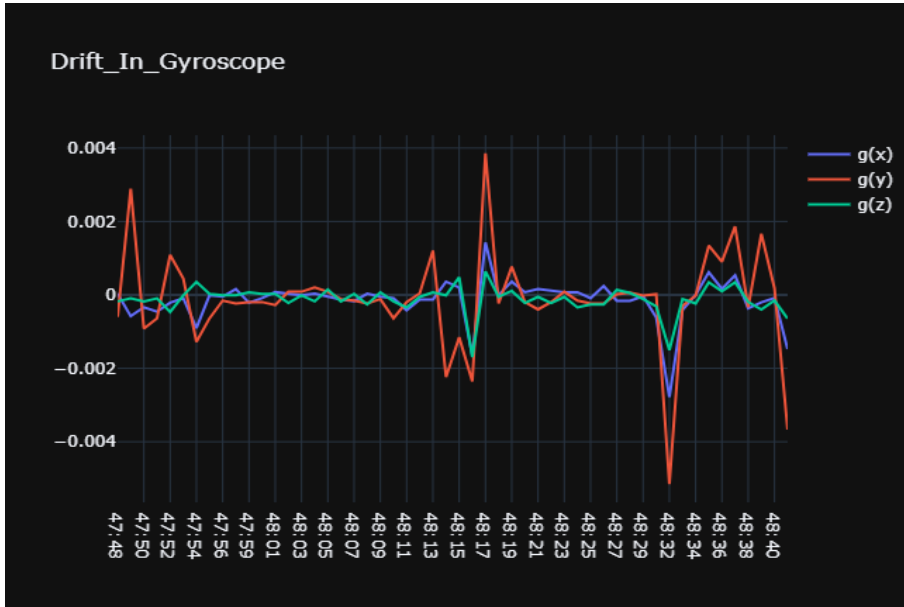


Figure 2: Drift Present In Gyroscope In Position 1



Figure 3: Drift Present In Gyroscope In Position 2

	$g(x)$	$g(y)$	$g(z)$
Test1	-1.42E-04	-0.000126156	-0.000120197
Test2	-1.42E-04	-0.00012560	-0.0001272
Test3	-1.34E-04	-0.00010906	-0.0001232
Test4	-1.50E-04	-0.0001812	-0.000120197
Test5	-1.44E-04	-0.00010914	-0.000132
Test6	-1.32E-04	-0.0001112	-0.0001231
Test7	-1.34E-04	-0.00010705	-0.0001316
Test8	-1.40E-04	-0.0001210	-0.0001307
Test9	-1.39E-04	-0.0001232	-0.0001295
Test10	-1.36E-04	-0.0001312	-0.0001204

Table 2: Average Drift Present In Gyroscope Sensor In Ten Different Positions

Axis	Average Drift Present
δ_x	-1.39E-04
δ_y	-0.00012
δ_z	-0.00013

Table 3: Final Values Of Drift Calculated In Gyroscope Sensor Along The Three Axes

uniformity and the independence of the sensor from external interferences. We did this drift test for 10 such positions and found that the average drift along the three axes is similar in each case, as expected (shown in Table 2). We thus finalize to set the final drift along the three axes as shown in Table 3. We followed the same steps as the gyroscope sensor to calculate the drift error present in the rotation vector sensor. Figure 4 is the illustration of the drift present in the rotation vector sensor when the phone is kept stationary. We calculated the drift present in the rotation vector sensor for 10 different positions as shown in Table 4 and then finalized the result of drift error as shown in Table 5.

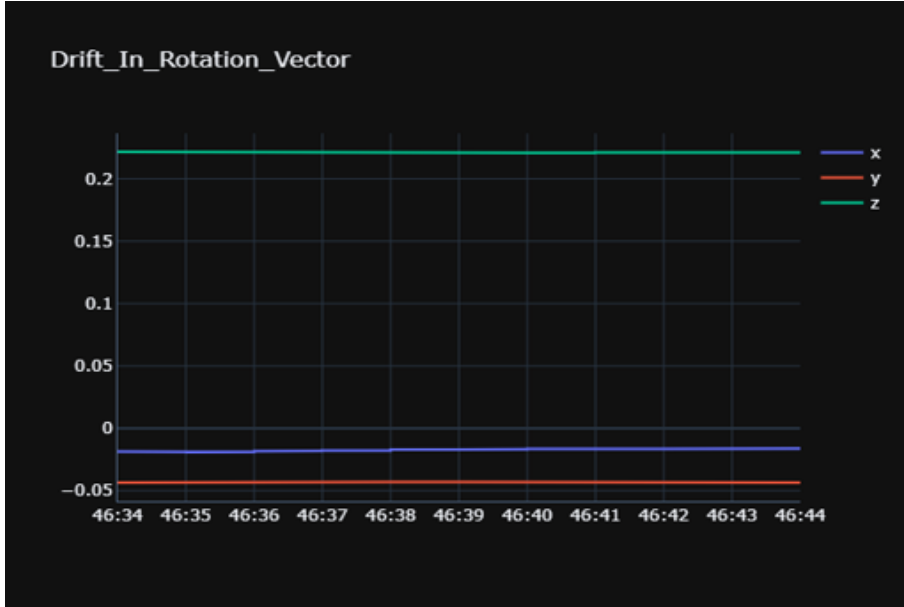


Figure 4: Drift Present In Rotation Vector

	$g(x)$	$g(y)$	$g(z)$
Test1	-0.018463405	-0.043468382	0.221780196
Test2	-0.018605834	-0.043389276	0.221735194
Test3	-0.018604318	-0.043432906	0.221782759
Test4	-0.018628433	-0.043329645	0.22167623
Test5	-0.018720627	-0.043225043	0.221588269
Test6	-0.018761281	-0.043086451	0.221447647
Test7	-0.018876439	-0.043091238	0.221486852
Test8	-0.018853227	-0.043159641	0.221555352
Test9	-0.018987553	-0.04302806	0.221450001
Test10	-0.018908154	-0.043013725	0.221410811

Table 4: Average Drift Present In Rotation Vector Sensor In Ten Different Positions

Axis	Average Drift Present
δ_x	-0.018740927
δ_y	-0.043222437
δ_z	0.221591331

Table 5: Final Values Of Drift Calculated In Rotation Vector Sensor Along The Three Axes

Axis	Correlation Coefficient
x	0.29772
y	0.23183
z	0.059551

Table 6: Correlation Values of Accelerometer Sensor Along The Three Axes

4.2 Accelerometer Sensor

We have plotted the original and calculated values of the accelerometer sensor along the x, y and z axes when the user was walking for about 1 minute (Figure 5 and Figure 6). We see that that the calculated values are very rapidly changing even when there is a slight or no change in the original values. This proves the susceptibility of the accelerometer to external magnetic interferences. We calculated the correlation between the original and the calculated values along the 3 axes, and observe that it is very low, as shown in Table 6. Thus, we infer that all the orientation angle calculations which make use of accelerometer sensor are valid only for a stationary mobile phone.

We observe that in this case, the results are very absurd. For little or no change in the original values, the new values change drastically. This clearly proves that using the accelerometer data alone would not give us accurate results.



Figure 5: Original Values of Accelerometer



Figure 6: Calculated Values of Accelerometer

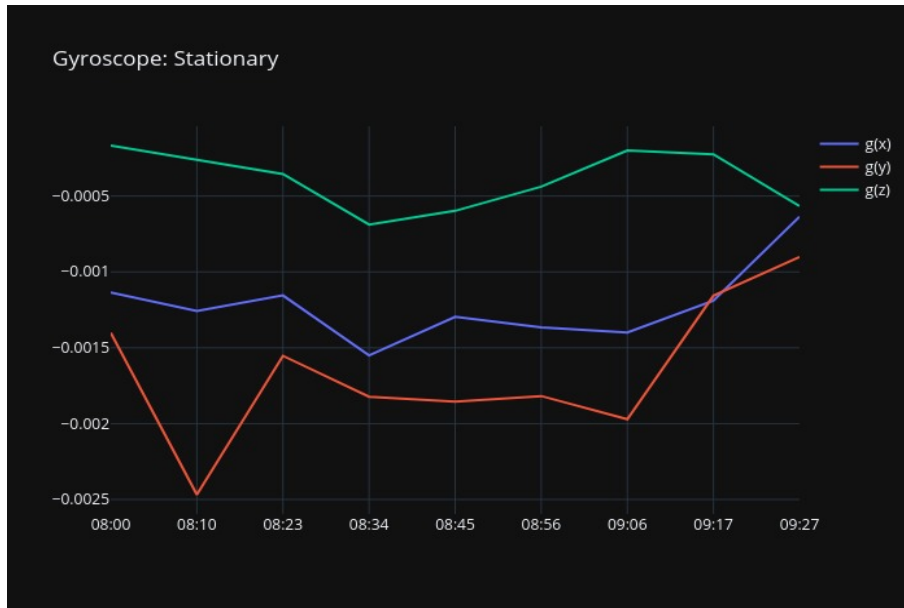


Figure 7: Original Values of Gyroscope When Stationary

4.3 Gyroscope Sensor

We test the gyroscope sensor to know the difference in the original and changed values when the phone is:

1. Stationary (Figure 7 and 8)
2. In motion (Figure 9 and 10)

For the first case, when the phone is kept stationary, the original values are obtained as shown in Figure 7. Now ideally, the values should have been constant throughout since we have applied drift correction but still we find that some drift always remain due to the highly sensitive nature of the sensor. But still, the results obtained in this case are much better than that of accelerometer sensor. Since the phone was stationary, and the gyroscope provides us with the angular rotation values about the three axes; so we observe here that the changed values (Figure 8) corresponding to the virtual reorientation of the phone are quite similar with the original values. This is hence, justified.

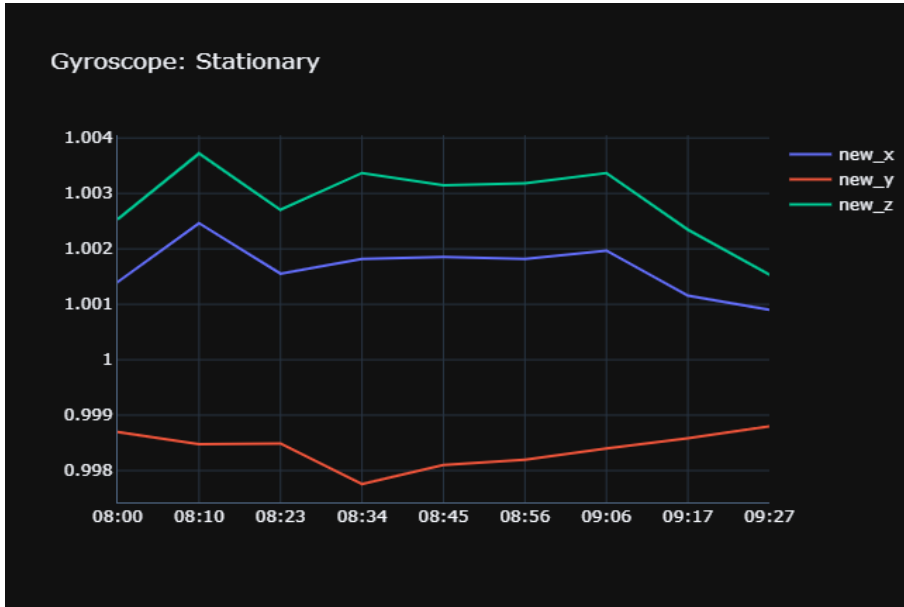


Figure 8: Calculated Values of Gyroscope When Stationary

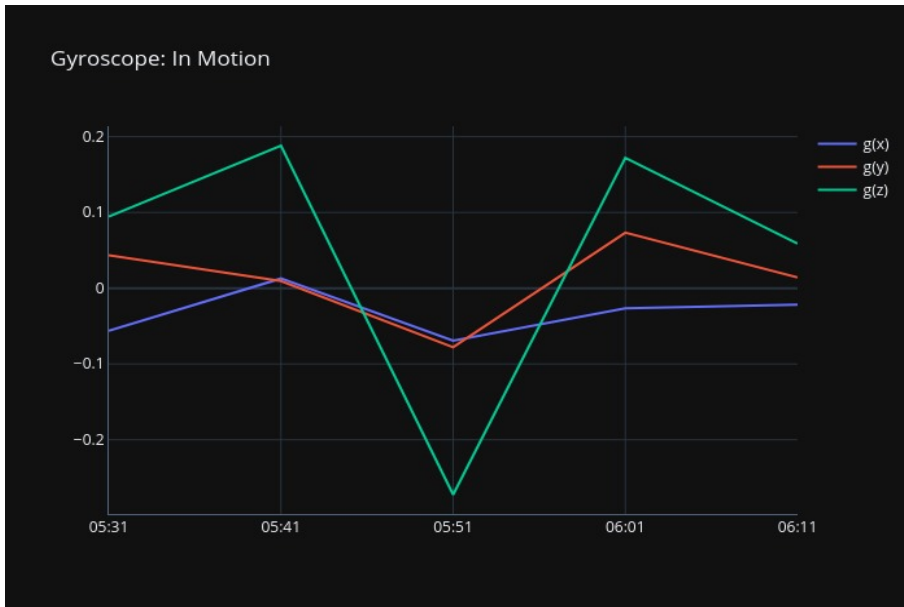


Figure 9: Original Values of Gyroscope When in Motion

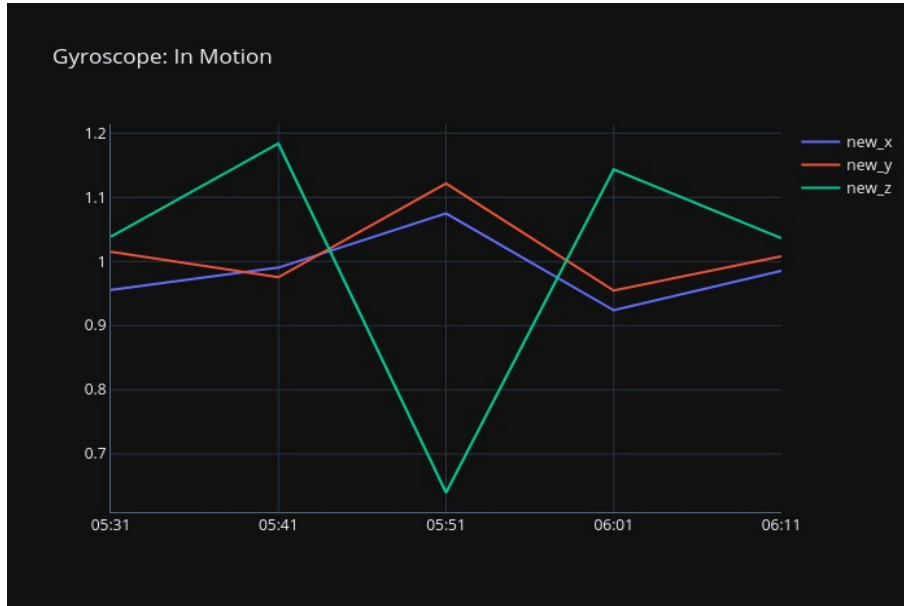


Figure 10: Calculated Values of Gyroscope When in Motion

For the second case, when the phone is in motion, the original values are obtained as shown in Figure 9. These values are obtained when the user is walking. In this case, we see that there is a lot of similarity between the actual (Figure 9) and calculated (Figure 10) values. It can be inferred that the gyroscope produces quite accurate results as compared to the accelerometer and orientation sensors.

We calculated the correlation coefficient between the original and calculated values of the gyroscope when the phone was kept stationary and also when it was in motion, as shown in Table 7 and 8. We observe that the correlation between the original and the calculated values in this case is much higher than the accelerometer sensor.

4.4 Rotation Vector Sensor

We test the rotation vector sensor to know the difference in the original and changed values when the phone is:

Axis	Correlation Coefficient
x	0.80349
y	0.86165
z	0.783

Table 7: Correlation Values of Gyroscope Sensor Along The Three Axes When Stationary

Axis	Correlation Coefficient
x	0.789781
y	0.80281
z	0.877

Table 8: Correlation Values of Gyroscope Sensor Along The Three Axes When In Motion

1. Stationary (Figure 11 and 12)
2. In motion (Figure 13 and 14)

When the phone is stationary, we observe that the similarity between the actual and calculated values increases even more. Here, we should note that the azimuth angle mark the rotation about the phone's z axis, the pitch angle mark the rotation about the phone's x axis and the roll angle mark the rotation about the phone's y axis. So the changes are corresponding to the same. So, we clearly observe that the error rate has decreased drastically here. When the phone is in motion, we again observe a very high similarity between the original values of the sensor and the calculated values of the sensor. We calculated the correlation coefficient between the original and calculated values of the rotation vector sensor when the phone was kept stationary and also when it was in motion, as shown in Table 9 and 10. We observe that the correlation between the original and the calculated values in this case is much higher than the accelerometer and the gyroscope sensor. This clearly proves that the rotation vector sensor is indeed very good in virtually reorienting our mobile devices.

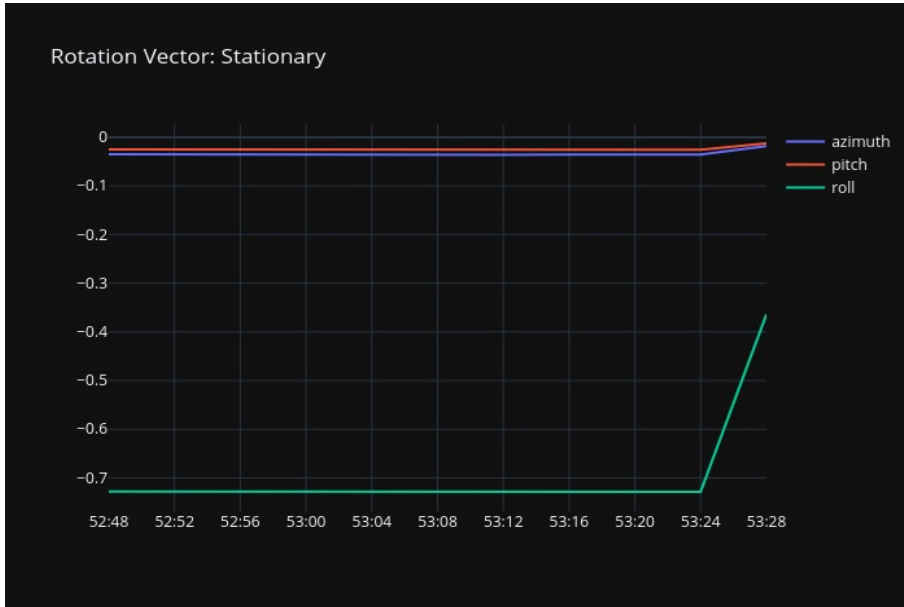


Figure 11: Original Values of Rotation Vector When Stationary

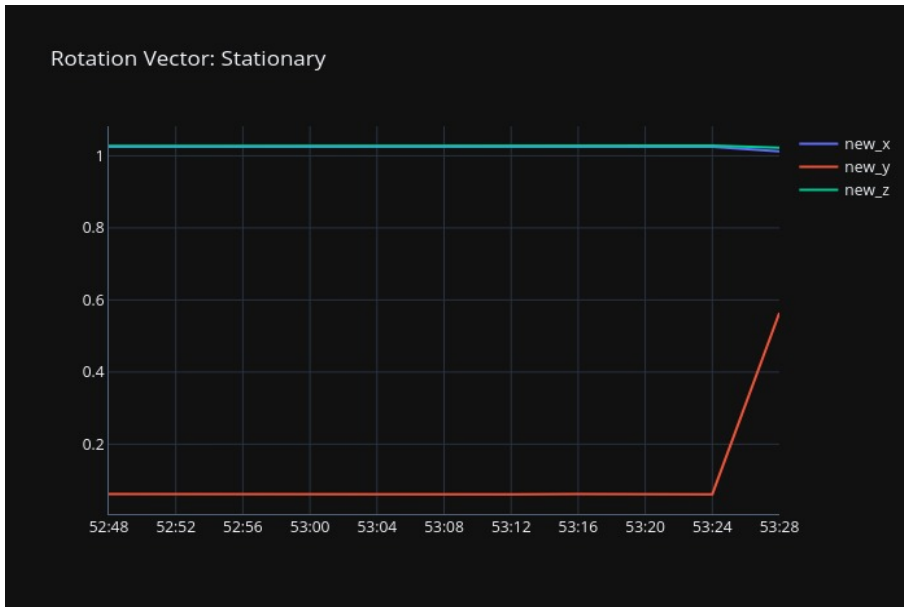


Figure 12: Calculated Values of Rotation Vector When Stationary

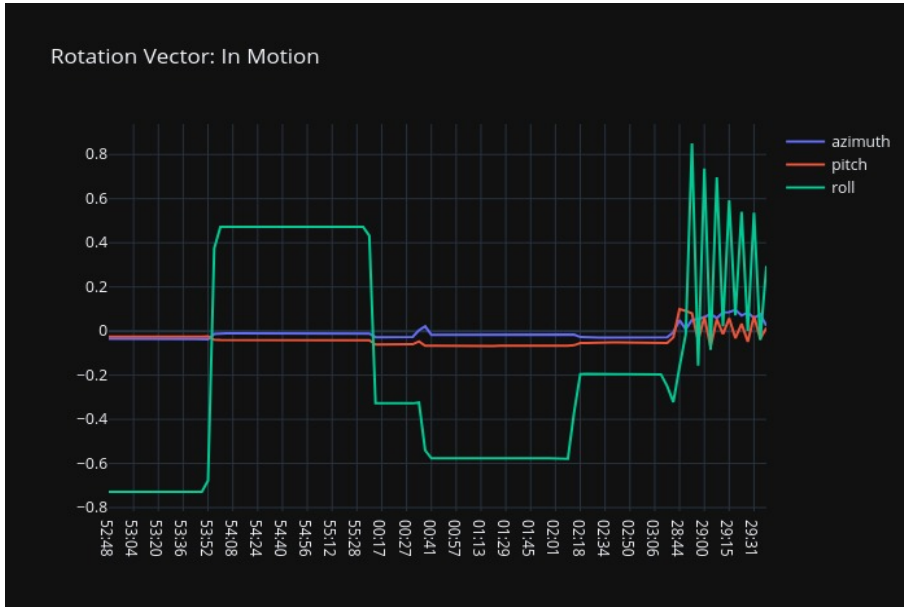


Figure 13: Original Values of Rotation Vector When in Motion

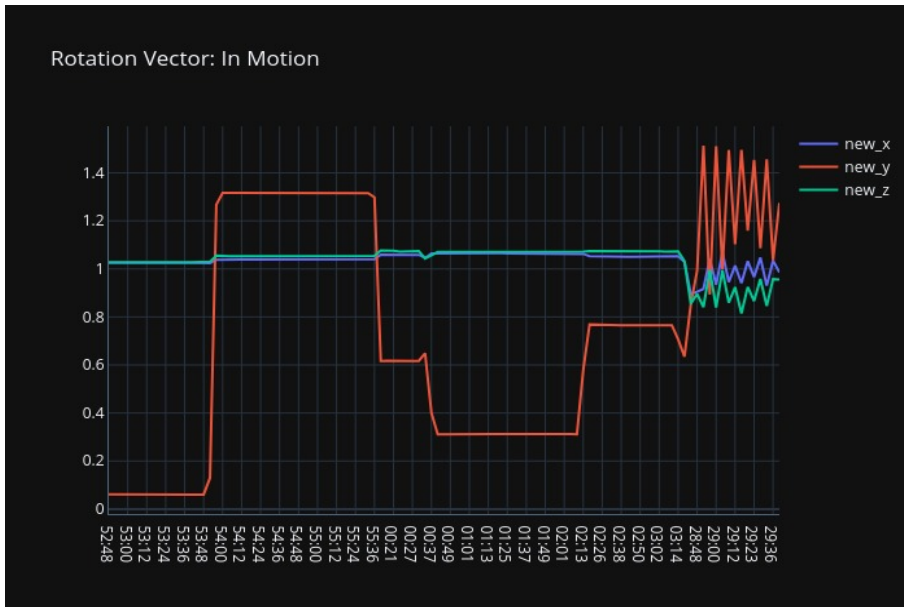


Figure 14: Calculated Values of Rotation Vector When in Motion

Axis	Correlation Coefficient
x	0.998134
y	0.99093
z	0.99614

Table 9: Correlation Values of Rotation Vector Sensor Along The Three Axes When Stationary

Axis	Correlation Coefficient
x	0.997683
y	0.98658
z	0.998866

Table 10: Correlation Values of Rotation Vector Sensor Along The Three Axes When In Motion

5 Conclusion and Future Work

We observed that accelerometer and orientation sensors are not effective in determining orientations due to the presence of magnetic interferences resulting from general use. We are able to determine the phone’s orientation while the phone’s actual orientation was constantly changing by integrating the angular velocity of gyroscope sensor and to an even better extent by the use of the rotation vector sensor. We have shown how we can virtually reorient our phone by applying rotational mathematics on these sensor data.

In an overall sense, any additional data that a mobile phone is able to collect can be analyzed in a meaningful and effective way if we are able to virtually reorient the phone and can get to know the correct orientation of the mobile phone at all times. The effective use of this data will have the potential to change our mobiles into much stronger and useful electronic devices.

As part of future work, we aim to test and apply this application to more scenarios like in a moving car, etc. We also aim to further utilize the capabilities of accelerometer, gyroscope and rotation vector sensor alongwith barometer and microphone sensor, if required, to perform accurate indoor localization of mobile phones.

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