# Experimental Evaluation of Mobile Phone Sensors

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**Abstract − Smart phone has become an important part of people's daily life. Most of current smart phone are equipped with a rich set of built-in sensors. The mobile applications such as geo-location based video annotation and indoor positioning require precise measurements from sensors. In addition, understanding the sensing performance of a smart phone device is helpful for implementing a mobile application that needs sensor data. This paper presents an experimental evaluation of key sensors in a state of the art smart phone – Google Nexus 4. The sensors chosen in the paper are accelerometer, gyroscope, magnetometer and GPS. Substantial tests have been executed to evaluate the sensors' accuracy, precision, maximum sampling frequency, sampling period jitter, energy consumption.**

*Keywords* − Smart phone, Sensor Fusion, Indoor Position, Video Tagging, Error analysis.

## I INTRODUCTION

In recently years, the usage of smart phone is accelerating. Smart phone has played an important role in people's daily life to provide various convenient services such as navigation.

In 2007, Apple Inc released the first generation iPhone. After that, the world has been changed. Advanced sensors have been widely applied to smart phones. Android have brought various sensors such as camera, GPS, accelerometer, magnetometer, gyroscope, microphone and so on to its platform.

The rich set of built-in sensors in smart phones enables a wide range of applications in various domains [1]. For example, researchers from National University of Singapore and University of Southern California developed a complementary approach of automatic tag generation and ranking for sensor-rich outdoor videos [2], which uses location data sampled from smart phones to model the viewable scenes of the video. Researchers from University of California and International Computer Science Institute developed an indoor localization application leveraging the sensing capabilities of current state of the smart phones [3].

Sensors will continue to be an important part of the smart phone platform. As the hardware specifications of smart phone devices improve, so do the number of available sensors and their quality. While this happens, users will continue to expect apps to use any existing and new sensors when possible. Therefore, understanding the performance of sensors is essential before using sensors in programs. In [4], the author evaluates accuracy of smart phone sensors for indoor positioning scenarios, whereas this paper focuses on general applications and presents a more comprehensive evaluation.

This paper provides a detailed performance evaluation of the most widely used sensors in smart phones, i.e. accelerometer, gyroscope, magnetometer and GPS. Google Nexus 4 is selected as the test device as it is the state of the art smart phone equipped with latest sensors. The tests focus on determining the accuracy, precision, maximum sampling frequency, sampling period jitter, and energy consumption of these chosen sensors.

Accuracy represents the closeness of the measured value to the actual value. Precision represents the closeness between the repeated measurements under the same condition. Maximum sampling frequency reflects the performance of the sensor. Sampling period jitter is the undesired deviation between sampling moment, which is important for some real-time applications. Energy consumption tests show battery usage of each sensor.

The rest of the paper is organized as follows. Section II introduces related work. Section III describes test methodology and test setup. Section IV presents test results and analysis. Finally, conclusions and further work are provided in Section V.

## II Related Work

In [4], the authors provide comprehensive tests on the accuracy of smart phone built-in sensors for indoor positioning systems. The device used in the tests is Google Nexus S which is the previous version of Nexus 4. They have tested inertial sensors (accelerometer, gyroscope and magnetometer), Wi-Fi and Bluetooth. Sampling frequency and energy efficiency are not considered in the paper.

Smart phone sensors have been used in various areas.

In paper [2], the authors utilize smart phone's built-in sensor meta-data to automatically generate tags for outdoor videos based on the geographic information acquired from the sensors. In [5], the authors provide a method to index and search videos based on geographic information. Traditional video searching is based on visual features. This paper proposes to search video using geographical location of the captured scene. The camera's location and orientation are saved which capturing the video. The captured scene is calculated based on the geospatial information.

Some Location Based Services (LBS) and Indoor Positioning Systems are implemented for mobile devices using the geospatial information offered by GPS, Wi-Fi radio, cellular communications radio, accelerometer and magnetometer. In [3], the authors explore the potential of Wi-Fi radio to provide indoor positioning functions. In [6], the authors tested and analyzed using ultrasound of mobile phones for indoor positioning.

With the various sensors which are equipped in smart phones, Augmented Reality can be implemented on the mobile platform with combining visual tracking and inertial measurement. In [7], the authors present a model-based hybrid tracking system for outdoor Augmented Reality for mobile devices. They use camera to determine the points of interest, and GPS and inertial sensors provided by an accelerometer and a gyroscope can achieve the self localization of smart phones. They combine several well-known approaches to provide a robust experience of Augmented Reality.

## III Methodology

### *a) Experiment Device*

Google Nexus 4 (LG E960) is chosen as the experimental device. It is the latest product of Google's Nexus devices with a wide range of state-of-the-art built-in sensors. It is equipped with the latest operation system –Android 4.2 Jelly Bean. The key specification is given in Table 1.

### *b) Android Sensor Platform*

Android is developed and managed by Google Inc. Recently it has become the world's most widely used platform for smart phones. The main reason for choosing Android as the experiment environment rather than any other mobile platforms, e.g. iOS or Windows Phone, is that it is an open-source platform for mobile devices.

Android uses a standard 3-axis coordinate system to express values for most built-in sensors including the accelerometer sensor and gyroscope sensor as shown in Fig. 1. When the phone is held in the upright position with the screen facing to the user, the Z axis points to the outside of the screen, the X axis is horizontal and points to the right, the Y axis is vertical and points up [8].

The coordinate system used for digital compass is different from the standard 3-axis coordinate system. Fig. 2 shows the coordinate system used by the getOrientation() [9]. When the phone is held in the upright position with the screen facing to the user, the X axis is tangential to the ground at the device's current location and roughly points to the west. The Y axis is tangential to the ground at the device's current location and points towards the magnetic North Pole. The Z axis points towards the centre of the Earth.

Table 1: Key specifications of Google Nexus 4

| **Processor** | **Qualcomm Snapdragon™ S4 Pro CPU** |
|---|---|
| **Operating System** | Android 4.2 (Jelly Bean) |
| **Memory** | 2 GB RAM, 16 GB flash memory |
| **Display** | 4.7" WXGA (1280*768) |
| **Battery** | 2100 mAh |
| **Sensors** | GPS<br>LGE Accelerometer Sensor<br>LGE Gyroscope Sensor<br>LGE Magnetometer Sensor<br>LGE Proximity Sensor<br>LGE Barometer Sensor<br>LGE Light Sensor<br>Gravity Sensor<br>Linear Acceleration Sensor<br>Microphone |

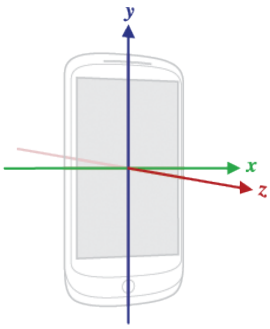


Fig. 1: Coordinate system used by the Acceleration Sensor and Gyroscope

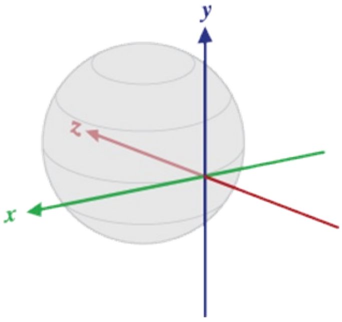


Fig. 2: Coordinate system used by the getOrientation()

*c) Test Procedures*

For accuracy and precision tests, the sensors are read repeatedly at each condition with the fastest sampling rate and the normal sampling rate (provided by the Android APIs) for a certain time. These tests are repeated a few times. The sampling frequency and energy consumption are recorded during the accuracy and precision tests.

The sensors that are evaluated in the paper are accelerometer, gyroscope, magnetometer, and GPS. The testing software is implemented in Java on the Android OS. The test procedures may be different for each sensor.

**Test procedure for the accelerometer sensor and the gyroscope sensor:**

The tests are carried out by placing the phone in the following 6 positions. For each position, the test is repeated 5 times under the fastest and normal sampling rate respectively.

1) Laying flat with the back on the table.
2) Laying flat with the screen on the table.
3) Standing vertical with the bottom on the table.
4) Standing vertical with the top on the table.
5) Standing vertical with the right side on the table.
6) Standing vertical with the left side on the table.

**Test procedure for the compass sensor:**

In order to avoid magnetic interference, the tests are executed outdoor. A commercial magnetic compass is used to get the actual orientation values. The tests are performed in 4 different positions. For each position, the test is repeated 3 times under the fastest and normal sampling rate respectively.

1) Laying flat with the back on the ground and point the top toward North.
2) Laying flat with the back on the ground and point the top toward East.
3) Laying flat with the back on the ground and point the top toward South.
4) Laying flat with the back on the ground and point the top toward West.

**Test procedure for the GPS sensor:**

The tests are executed outdoors. A commercial professional GPS device is used to acquire the actual GPS longitude and latitude of a specific place. Afterwards, the phone is laid flat on the same place and tested 5 times under the fastest sampling rate.

## IV Test Results

*a) Accelerometer*

The accelerometer sensor measures the acceleration force applied to the device, e.g. the force of gravity. It can provide measurements on all three physical axes (X, Y, and Z) of the device. The common usages of accelerometers in mobile phones include detecting motions and determining tilts.

Ideally, when the phone is still, the accelerometer readings are 9.81 $m/s^2$ (the force of gravity). Suppose the phone is laying flat with its back on a table, the acceleration value of phone's Z axis should be 9.81 $m/s^2$ and the readings of the other two axes should be 0 $m/s^2$.

**Accuracy tests with the fastest sampling rate:**

In the tests, the phone is placed on a table with the orientations defined in the previous section. The accelerometer readings are recorded for around 10 seconds with the fastest rate (SensorManager.SENSOR_DELAY_FASTEST).

Fig. 3 shows the phone's actual accelerometer readings for the X, Y and the Z axis while laying flat on the table. The readings of the X axis are invisible on Fig. 3 because it is covered by the readings of Y axis. The same test is repeated for 5 times and the results of the other 4 tests are similar and therefore are not shown in the paper. The test results for the other orientations are not shown in the paper because they are all similar.

Fig. 3 shows the values of the X axis and Y axis are approximately 0 m/s$^2$ and the values of Z axis are around 9.81 m/s$^2$.

Fig. 4 shows the statistics analysis results on the absolute errors of the test results. It shows that the deviations between measured values and standard values range from 0.003 to 0.432 m/s$^2$. The most important error source of an accelerometer is the bias. The bias is the offset of its output signal from the true value, in m/s$^2$.

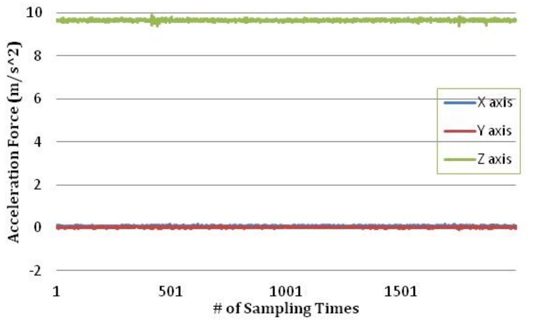


Fig. 3: The output of Acceleration Sensor (Sampling Rate: Fastest)

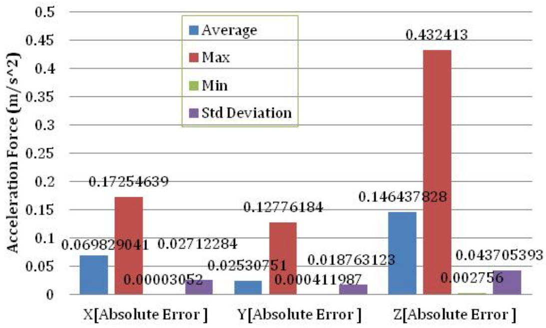


Fig. 4: Absolute Error of Accelerometer Sensor (Sampling Rate: Fastest)

**Precision tests with the fastest sampling rate:**

The stability of the accelerometer outputs is also an important factor to evaluate the sensor's quality. Fig. 5 only presents the values of Z axis in Fig. 3 in order to clearly show the distribution of the sensor readings. It shows that the values of Z axis vary between 9.55 m/s$^2$ and 9.75 m/s$^2$. The statistics analysis results for X, Y, and Z axis are given in Table 2. The standard deviations of all axes are between 0.025 and 0.044 m/s$^2$.

**Sampling frequency tests with fastest sampling rate:**

The aim of these tests is to determine the maximum possible sampling frequency of the accelerometer sensor and the accuracy of the sampling time. In Android, the sensor events are generated every time the sensor values changes. As there are no absolute still objects, the sensor events should be triggered with the maximum sampling frequency of the sensor. Fig. 6 shows all the sampling intervals between every two readings. It shows that most sampling frequencies of the acceleration sensor are around 5035863.812 nanoseconds. The maximum sampling frequency is 5360128 nanoseconds as shown in Table 3. Fig. 6 shows that the sampling frequency is approximately 5030000 nanoseconds and 5040000 nanoseconds alternative when the phone is laying flat on the table, so the standard deviation is very big at this position. This phenomenon didn't happen in other positions.

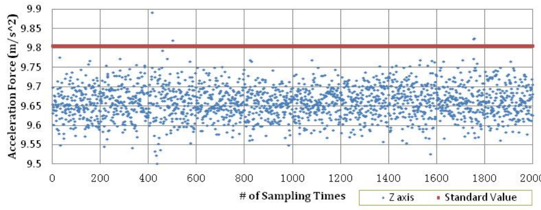


Fig. 5: The measured values of Z axis compare with Standard Value

Table 2: Acceleration Sensor Statistics (Sampling Rate: Fastest)

| Axis | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| X[m/s$^2$] | 0.069713165 | 0.17254639 | -0.0262146 | 0.027419446 |
| Y[m/s$^2$] | 0.0187099 | 0.12776184 | -0.07814026 | 0.025349749 |
| Z[m/s$^2$] | 9.66034516 | 9.891968 | 9.374237 | 0.04414875 |

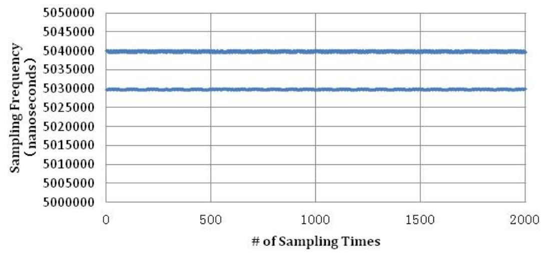


Fig. 6: Sampling frequency (Sampling Rate: Fastest)

Table 3: Sampling frequency statistics (Sampling Rate: Fastest)

| | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| Sampling Frequency | 5035862.955 | 5360128 | 4969984 | 11522.9357 |

**Accuracy tests with the normal sampling rate:**

The above tests are repeated at the normal sampling rate. The setting in Android API is SensorManager.SENSOR_DELAY_NORMAL. As the sampling rate in the normal mode is slower than that in the fastest mode, each test lasts 30 seconds which are longer than the tests in the fastest mode (10 seconds). The test is repeated 5 times. Only one test result is shown because the other 4 tests have similar results.

Fig. 7 shows the output of accelerometer sensor under the normal sampling rate. Values of the X axis are invisible on the graph because it is covered by the values of the Y axis. The results are similar to Fig. 3 except the sampling frequency is less (150 times).

The deviations between measured values and standard values range from 0.003 to 0.215 $m/s^2$ as shown in Fig. 8. The standard deviation for absolute error under normal sampling rate is similar to Fig. 4 (fastest sampling rate). Comparing Fig. 4 and Fig. 8, it shows that there is no significant accuracy difference while the sensor is working in the normal sampling rate and in the fast sampling rate.

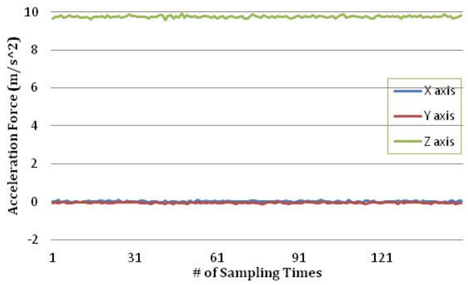


Fig. 7: The output of Acceleration Sensor (Sampling Rate: Normal)

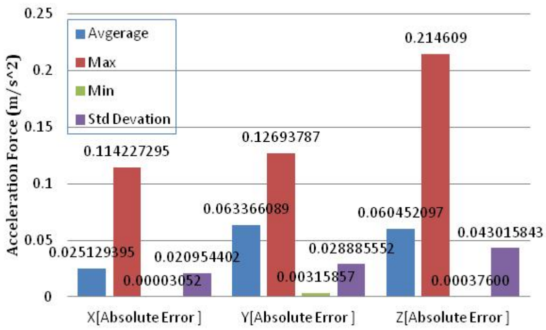


Fig. 8: Absolute Error of Acceleration Sensor (Sampling Rate: Normal)

**Precision tests with the normal sampling rate:**

The standard deviation of accelerometer sensor under normal rate is shown in Table 4. The standard deviation of accelerometer sensor under normal sampling rate is higher than the standard deviation under fastest rate for each axis. The difference is 0.01. However, the sampling numbers under fastest rate is much more than the one under the normal rate (the sampling number under fastest rate is 2000, whereas it is 150 under normal rate). Therefore it is not fair to say that accelerometer sensor in the fastest sampling rate is more stable than that in the normal sampling rate.

Table 4: Acceleration Sensor Statistics (Sample Rate: Normal)

| Axis | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| X[$m/s^2$] | 0.011300049 | 0.114227295 | -0.054779053 | 0.030761 |
| Y[$m/s^2$] | -0.063366089 | -0.003158569 | -0.12693787 | 0.028886 |
| Z[$m/s^2$] | 9.754112503 | 9.901489 | 9.592041 | 0.052446 |

**Sampling frequency tests with normal sampling rate:**

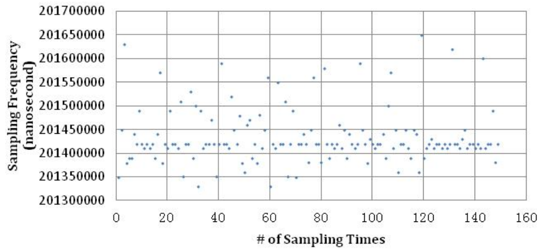


Fig. 9: Sampling frequency (Sampling Rate: Normal)

The sampling frequency is shown in Fig. 9. It is approximately every 201434422 nanosecond under normal rate which is a quarter of the sampling frequency under fastest rate.

*b) Gyroscope*

Gyroscope sensor measures a device's rate of rotation in rad/s around each of the three physical axes (X, Y, and Z defined in Fig. 1). It is used for detection rotation around X, Y and Z axis. When the device is still, the gyroscope readings should be 0 radians per second. In the test results, the output is converted from rad/s to degree/s for easier understanding.

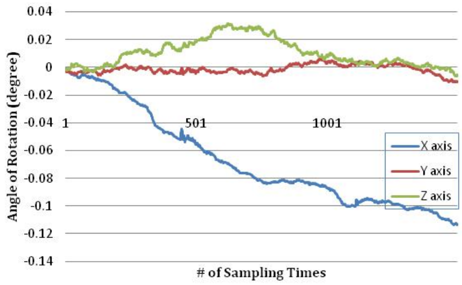


Fig. 10: The output of Gyroscope Sensor (Sampling Rate: Fastest)

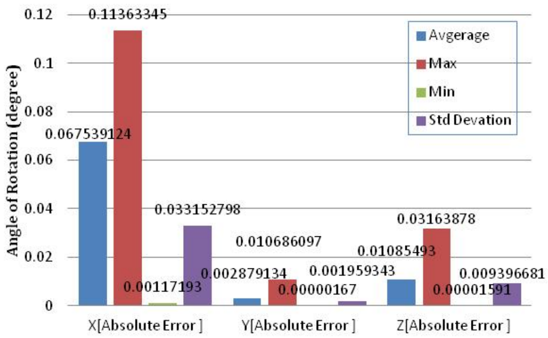


Fig. 11: Absolute Error of Gyroscope Sensor (Sampling Rate: Fastest)

The tests are carried out with the procedure defined in Section II. Six phone orientations are tested. Only parts of the test results are shown in the paper because other test results are similar. In the first test, the phone is laid on the table still. The samples are recorded during a period of approximately 10 seconds under the fastest rate defined by Android (SensorManager.SENSOR_DELAY_FASTEST).

**Accuracy tests with the fastest sampling rate:**

The Fig. 10 shows the test results for the X, Y, and Z axis without compensating for the bias error introduced by the offset: during 10 seconds, it has accumulated an angle around -0.12 degrees on the X axis. The deviations between measured values and standard values range from 0.001 to 0.114 degrees as shown in Fig.11.

**Precision tests with the fastest sampling rate:**

The precision of gyroscope is better than the accuracy. The standard deviation is 0.033, 0.003, and 0.009 for X, Y, and Z axis respectively (Table 5).

Table 5: Gyroscope Statistics (Sampling Rate: Fastest)

| Axis | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| X[degree] | -0.067539124 | -0.001171928 | -0.11363345 | 0.033153 |
| Y[degree] | -0.001317168 | 0.006254597 | -0.010686097 | 0.003225 |
| Z[degree] | 0.010424796 | 0.03163878 | -0.006650992 | 0.009872 |

**Sampling frequency tests:**

The sampling frequency of the gyroscope sensor under fastest rate and normal rate are shown in Fig.12 and Fig.13.

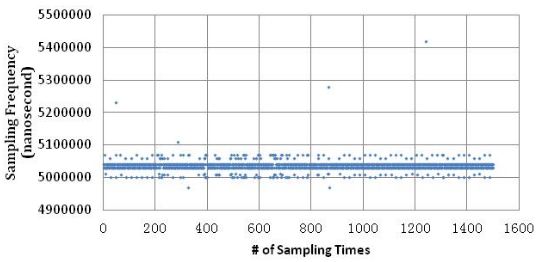


Fig. 12: Sampling frequency (Sampling Rate: Fastest)

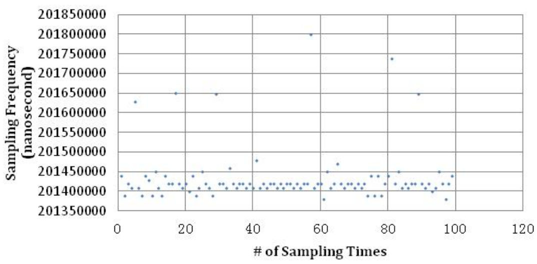


Fig. 13: Sampling frequency (Sampling Rate: Normal)

Table 6: Sampling frequency statistics (Sampling Rate: Fastest)

| Sampling Frequency | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| | 5035857.121 | 5830144 | 4239872 | 34535.71 |

Table 7: Sampling frequency statistics (Sampling Rate: Normal)

| Sampling Frequency | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| | 201434445.6 | 201799936 | 201379840 | 68435.95 |

The standard deviation of sampling frequency under normal rate is double than that under fastest rate as shown in Table 6 and Table 7. This means that the sampling frequency under fastest rate is more stable than that under normal rate. The sampling frequency under normal rate is a quarter of the sampling frequency under fastest rate as accelerometer sensor.

*c) Digital Compass*

In Android, the orientation information can be acquired using getOrientation() method. The getOrientation() return an array of values. The value[0] azimuth is what we used to present the North.

**Accuracy tests:**

The North is recorded 3 times using this method under fastest sampling rate and normal sampling rate. The result of one test under fastest sampling rate is shown in Fig. 14. A large proportion of Azimuth values are 0 degree that means the smart phone points toward North. But numbers of Azimuth values are approximate 90 degrees and rest Azimuth values are range from -170 to 170 degrees. The test results of the other two tests are almost the same. These results represent that the accelerometer sensor and magnetometer sensor used by the getOrientation() method under fastest rate is very unstable. So we ignore the sampling data under fastest rate and only record the energy consumption.

Fig. 15 shows the result of one test under normal sampling rate. There is approximately 3 degrees deviation between the measured values and the standard value. The absolute error is stable as shown in Fig. 16.

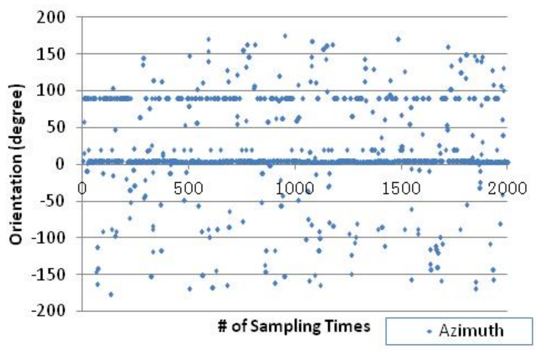


Fig. 14: The output of getOrientation() (Sampling Rate: Fastest)

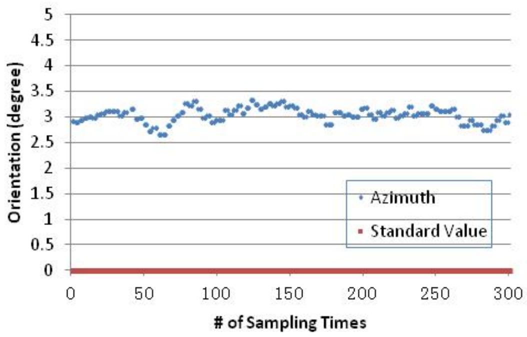


Fig. 15: The output of getOrientation() (Sampling Rate: Normal)

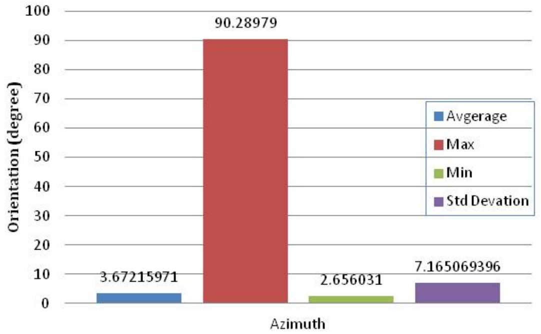


Fig. 16: Absolute Error of getOrientation() (Sampling Rate: Normal)

**Precision tests with the normal sampling rate:**

Table 8 shows the statistics of the output of getOrientation(). The standard deviation is about 7.17.

Table 8: getOrientation() statistics when the phone point toward North (Sampling Rate: Normal)

| Axis | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| X[degree] | 3.67216 | 90.28979 | 2.656031 | 7.165069 |

**Sampling frequency tests:**

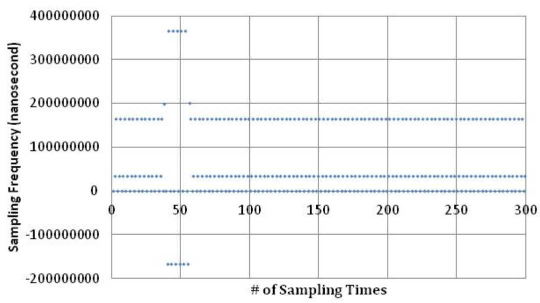


Fig. 17: Sampling frequency (Sampling Rate: Normal)

Table 9: Sampling frequency statistics (Sampling Rate: Normal)

| Sampling Frequency | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| | 66816455 | 366760192 | -166020096 | 86769662 |

The sampling frequency of the digital compass under normal rate is shown in Fig. 17. The getOrientaiton() method reads three times for one value. The first sampling interval when the sensor's values changed is approximate 165400000 nanoseconds and the second one is approximate 680000 nanoseconds and the last one is approximate 35300000 nanoseconds. Then the sensors read a new value three times repeatedly like this.

*d) GPS*

Android can locate the phone using GPS and Network Location Provider. This paper only focuses on the GPS sensor.

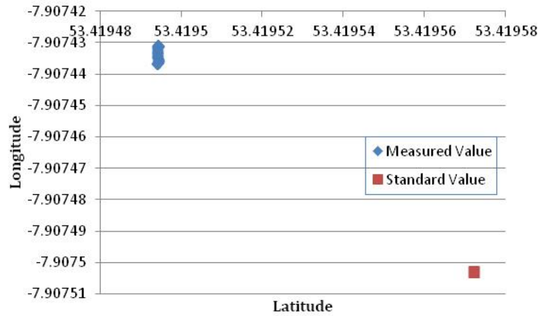


Fig. 18: The measured Values and the Standard Value of GPS

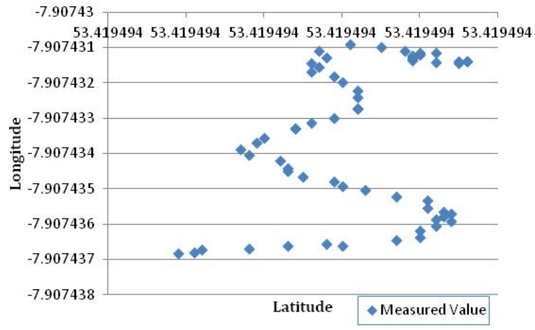


Fig. 19: The output of the phone GPS sensor

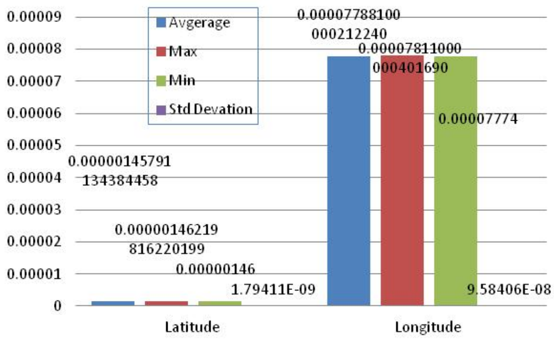


Fig. 20: Absolute Error of GPS

**Accuracy tests:**

During the tests, a specific outdoor place is chosen. Its longitude and latitude is recorded using professional GPS device and the phone's GPS sensor respectively. The results are shown in Fig. 18. Through calculating the measured values and the standard values, the difference between the two measurements is between 8 to 10 meters.

Fig. 20 shows that the deviation of longitude is much larger than the deviation of latitude. Therefore, the measurements on latitude are more accurate.

**Precision tests:**

The standard deviation of longitude and latitude are shown in Table 10. The measurements from latitude are more accurate and stable than those for longitude.

Table 10: GPS measurement statistics

| | Average | Max | Min | Std Deviation |
|---|---|---|---|---|
| Latitude | 53.41949412 | 53.41949426 | 53.41949389 | 9.58406E-08 |
| Longitude | -7.907433605 | -7.9074309 | -7.90743683 | 2.08268E-06 |

**Sampling frequency tests:**

Android SDK needs programmers to manually setup sampling frequency. The minimum time interval between notifications and the minimum change in distance between notifications are both set to zero in the test program. It requests location notifications as fast as possible. The sampling frequency is a constant (1 second) in this sampling rate. Therefore the sampling frequency is a straight line if it is drew in the figure.

*e) Energy Consumption*

During the energy consumption tests, the phone's Wi-Fi and Bluetooth are turned off and the screen brightness is set to the lowest. All Android apps are closed except the testing application. The testing app runs for 1 hour and the battery level changes are recorded. The test is repeated five times with the fastest sampling rate and normal sampling rate respectively for each sensor: accelerometer, gyroscope, magnetometer and GPS. The battery capacity of Google Nexus 4 is 2100 mAh. Table 11 shows the results of energy consumption for each sensor after running 1 hour in the experimental environment.

Table 11: Energy Consumption for each sensor

| Frequency | Accelerometer | Gyroscope | Magnetometer | GPS |
|---|---|---|---|---|
| Fastest | 14%, 294 mAh | 12%, 252 mAh | 14%, 294 mAh | 11%, 231 mAh |
| Normal | 10%, 210 mAh | 9%, 189 mAh | 9%, 189 mAh | N/A |

## V CONCLUSION AND FUTURE WORK

This paper evaluates sensor performance of the state of the art smart phones and focuses on accuracy, precision, maximum sampling frequency, sampling period jitter, and energy consumption. The sensors that are evaluated in the paper are accelerometer, gyroscope, magnetometer, and GPS.

The test results show that the built-in accelerometer sensor and gyroscope sensor is very stable. There are only approximately 0.1-0.8 unit deviations between the measured value and the real value. The compass has a bigger deviation which is approximately 3 degrees in the normal sampling rate. It can show a rough orientation of the phone. However, the compass is nearly not working in the fastest sampling rate. In an outdoor environment, the GPS sensor is able to determine its location with a deviation which is no more than 10 meters.

The energy consumption of each sensor is also provided in this paper. It can provide a reference to app developers to decide sensor usage strategies for different applications.

In further, we will do some the similar experiments with other sensors such as proximity sensor and we will test the same sensors in different smart phones. We will also consider performing the test when the device is hold in hand while people walking as an optional record method.

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