Smart Physics with Smartphones

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Version 1; April 4, 2016

The Smart Physics lab has been designed to introduce the students to new methods of data collection using commonly available consumer devices. This primer is meant as a general introduction to the experiments in the Smart Physics Lab in which smartphones are used to study several principles of physics. The aim is to explain the general methodology of collecting motion data for experiments in the smart physics lab using a smartphone. For specific experiments, one may refer to the individual experiment manuals that are uploaded on our website.

1 Data Collection Using Smartphones

These days smartphones come packed with a variety of sensors such as an accelerometer (force sensor), gyroscope (angular velocity sensor), touch screen, ambient light sensor, proximity sensor, magnetometer, barometer, heart pulse rate monitor and even a blood oxygen level meter. We can use freeware applications easily available on online application stores to collect and record data being reported by these sensors. In this document, we tend to focus on the inertial motion sensors namely the linear motion sensor (accelerometer) and the rotational motion sensor (gyroscope).

The coordinate system of a smartphone is fixed and rotations about each axis are defined as shown in Figure (1).

1.1 Accelerometer

An accelerometer is basically a linear motion sensor. They are sensitive to both linear acceleration and the local gravitational field. Accelerometers have now become indigenous in the automotive industry but have also found their applications in the consumer electronics. Almost all modern smartphones now ship with an accelerometer sensor. For example, the linear sensing provides the smartphone information about its motion and thus taps or shakes can be detected. Similarly, orientation can be determined by the smartphone's sensitivity to the local gravitational field.

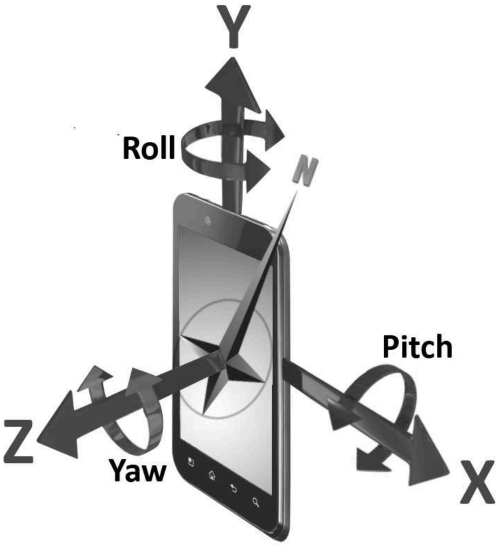

Figure 1: The fixed coordinate system for smartphones (reproduced with permission from *Yole Développement*)

The basic principle of operation of an accelerometer is the second law of motion. An accelerometer comprises of a proof mass which is attached to nearly ideal springs and free to move about its mean position. When a force is applied, the accelerometer reports the force required to maintain the proof mass within the accelerometer casing. The accelerometer consists of a proof mass attached through (nearly) ideal springs to a substrate (base). The proof mass can only move up and down. The movable plates (proof mass) and fixed plates (case) construct the capacitors. Capacitive sensing is independent of the base material and relies on the variation of capacitance when the geometry of the capacitor is changing. Thus, a change in distance between the plates creates an electric signal which is detected and fed to a conditioning circuit and the output is then reported in the desired units. In a triaxial accelerometer, there are simply three one dimensional sensors oriented orthogonal to each other.

The data from the accelerometer is conventionally reported in units of g ($1g = 9.81$ m/s^2). We can simply multiply the reading by 9.81 to convert them to appropriate units of m/s^2. The accelerometer reports a value of $1g$ along the z-axis and 0 along the x and y axes when lying at rest face up on a flat table. This is the initial condition and calibration of any accelerometer in good working condition should give you these results. The gravity vector thus reported is used as a reference for all other linear motion sensing.

We use the `Physics Toolbox Accelerometer` app to acquire data reported by the accelerometer along the three axes. The recorded data is transferred to the computer via email or using a data cable. The values contain a component of acceleration due to gravity which needs to be eliminated prior to further processing to obtain the real acceleration.

A simple example to understand the readings on an accelerometer is to measure the accelerations of a moving elevator as shown in figure (2). The smartphone is placed on the floor of the car facing up

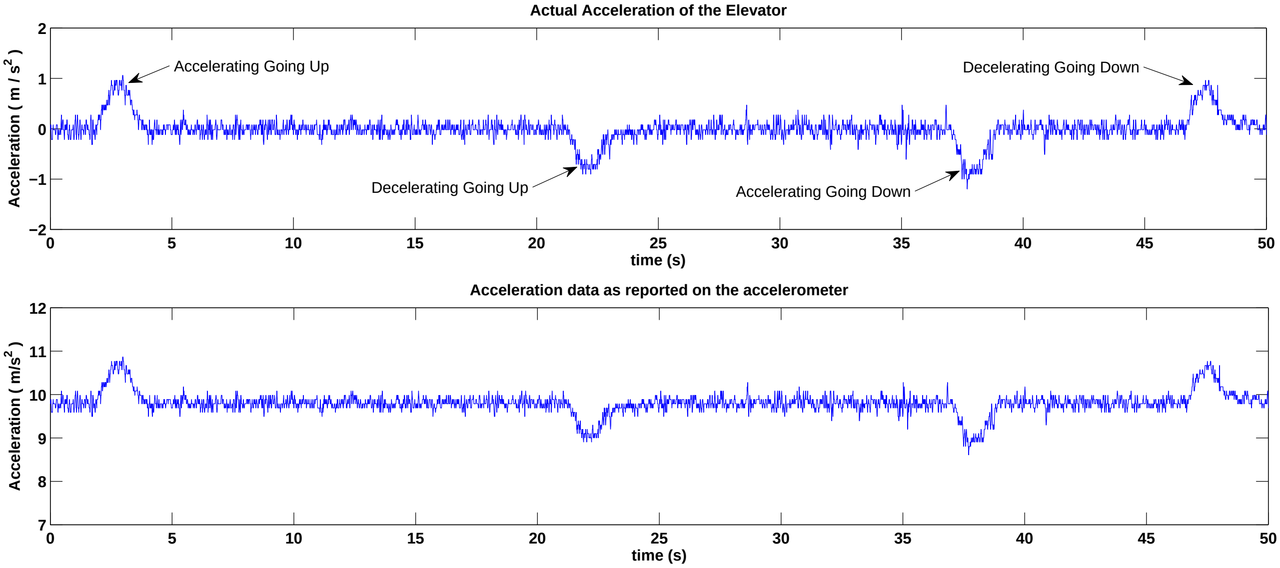

Figure 2: Accelerometer data for a moving elevator.

so that it reports an upward acceleration of 9.81 m/s^2. Going up, the elevator starts from rest and accelerates upwards and stops accelerating when it reaches a threshold speed. Before it reaches the destination floor, it decelerates and then comes to a stop. When going down, the same is repeated again in the opposite direction. The rider feels pushed down when the elevator is accelerating upwards. This is of course due to the inertia of the rider (or smartphone in this case) but the effective acceleration reported on the accelerometer provides us a sense of the push or a pull that we feel. The accelerometer also reports the acceleration due to gravity and data must be adjusted for this offset before further analysis is undertaken. We can also observe that the acceleration is not constant throughout the accelerating region contrary to the common conception. We can also notice that the elevator only accelerates to a maximum of about 1 m/s^2. This can explain a safety precaution so as to prevent nausea and other medical conditions that may be induced by these changes in acceleration. This simple example provides a very crude introduction to accelerometer readings and how it can be used to demonstrate common physical phenomena.

A word of caution here. We need to be careful when trying to use the acceleration data in laboratory experiments. As we have already seen, the accelerometer only reports data along its own fixed coordinate system. During the experiments, this fixed coordinate system may be undergoing several transformations with respect to the lab frame. In fact, the equivalence principle renders it impossible to determine experimentally whether a system is subject to a gravitational field or a non-inertial field as a result of coordinate transformations.

1.2 Gyroscope

A gyroscope is a rotational motion sensing device. Gyrsoscopes measure rotation about a fixed axis and the smartphone's gyroscope comprises a small resonating mass which is shifted as the angular velocity changes. This movement is converted into very low current electrical signals which are amplified and read using a host microcontroller. Gyroscopes report data in units of rad/s. They are very sensitive to changes in orientation and even low-quality gyroscopes can sense changes us small as 0.01 rad/s.

However, we need to determine the axis about which we are measuring rotation. The smartphone's gyroscope reports rotations about all of the three fixed coordinate axes. It is often useful to invoke the parallel axis theorem to make sense of the data being reported by the gyroscope sensor. For example, if we attach a smartphone to the periphery of a bicycle wheel and rotate, the rotations are about the axle which in turn defines the axis of rotation. However, using the parallel axis theorem, we can easily conclude that the wheel's rotation is the same as if the smartphone is rotating about the axis parallel to the axle (or the bicycle's axis of rotation). Analyzing the system and using such clever bits of knowledge (that one learns in physics) often makes life very easy for the experimental physicist.

2 Analyzing Data

Once the motion data has been extracted from the smartphone, we need to analyze it using numerical techniques in MATLAB. For an introduction to some very important techniques, see the "Analyzing Data" section in the primer "Smart Physics with Video Tracking".

3 What are we measuring?

3.1 Uncertainty Analysis

The type A uncertainty in readings from both sensors can be minimized by taking multiple readings and evaluated using the statistical methods for treating data. For type B uncertainties, we need to check the datasheets and then make the decision.

Check the datasheet for the smartphone's accelerometer and gyroscope modules to get the accuracy of the device. For example, the smartphone used in these experiments shipped with a BMA050 3-axis Accelerometer module from Bosch with a maximum operating range of 32 ms^{-2} and an accuracy of 0.0039 ms^{-2}. We can use double this value with 95% confidence in our uncertainty calculations. Similarly, the gyroscope module is an MPU3050c gyroscope sensor from Invensensor with a max range of 34.91 rad s^{-1} and an accuracy of 0.01 rad s^{-1}. We can use double this value of accuracy as our type B uncertainty in the readings from gyroscope.

The two types of uncertainties must be combined to give the total uncertainty in the readings. The accelerometer is very sensitive to vibrations and usually the type A uncertainties dominate. On the other hand, the gyroscope is very sensitive to rotations and usually the type B uncertainty dominates.

4 Further Reading and References

1. M. Monteiro, C. Cabezay, A.C. Marti, "*Acceleration Measurements Using Smartphone Sensors: Dealing with the Equivalence Principle*", arXiv:1406.3867v1 [physics.ed-ph] 15 Jun 2014.
2. M. Pedley, "*Tilt Sensing Using a Three-Axis Accelerometer*", Freescale Semiconductor Application Note AN3461, *Rev*.6, (March 2013).
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