Demo: Instant Phone Attitude Estimation and Its Applications

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ABSTRACT
The phone attitude is an essential input to many smartphone applications. Based on in-depth understanding of the nature of the MEMS gyroscope and other IMU sensors, we propose $A^3$—an accurate and automatic attitude detector for commodity smartphones. In this demo, we show the performance of our attitude tracking algorithm and its usability in attitude-based mobile applications.

Categories and Subject Descriptors
C.4 [Performance of Systems]: Modeling techniques. Performance attributes; C.5.3 [Computer System Implementation]: Portable devices

Keywords
Mobile Phone Attitude, Gyroscope, IMU Sensors, Attitude-based Applications

1. INTRODUCTION
Smartphones are becoming more and more powerful and provide a good platform for mobile applications [9, 4, 3, 2]. The phone attitude [8] gives the 3D orientation of the phone with respect to the earth coordinate system. It is an essential input to many mobile applications such as mobile gaming, gesture and activity recognition [5], 3D photography, dead reckoning based localization and navigation [7, 6, 1], etc.

In this demo, we show the performance of our attitude tracking algorithm and the attitude-based mobile applications. The design details of our algorithm are presented in our MobisCom paper [8] and we briefly introduce the design principles here. The phone attitude can be estimated based on the readings of three IMU (Inertial Measurement Unit) sensors, i.e., gyroscope, compass and accelerometer. We follow the device specification and conduct controlled experiments to investigate how different environmental factors impact on the gyroscope performance and how the best accuracy can be achieved in an appropriate condition range.

We also characterize the nature of the accelerometer and compass sensor to understand their performance in various conditions. Based on the comprehensive study, we propose to estimate the phone attitude primarily based on the gyroscope output, i.e., the 3-axis angular velocities, but also incorporate the compass and the accelerometer for opportunistic calibration. The three types of IMU sensors are of different natures and their accuracy varies in different condition ranges. In particular, the gyroscope provides a cumulative estimation of the attitude through continuous integration on angular velocities that is accurate in general but suffers from error accumulation. On the other hand, the compass sensor and accelerometer provide instantaneous attitude estimation which is independent of previous states but the accuracy highly depends on the instant environment dynamics and phone motions. We develop a practical approach that calibrates the cumulative gyroscope estimation when we have higher confidence in compass and accelerometer readings. In this work we propose a “opportunistic calibration” technique that looks at the concordance of the three types of sensors in estimating short period attitude changes. High consistency indicates high instantaneous confidence of the compass and gravity outputs and thus a positive calibration opportunity. Sufficient calibration opportunites can be identified using this approach.

2. PHONE ATTITUDE FROM IMU SENSORS
In this section, we introduce the basic operations performed on the readings of the IMU sensors to derive the accurate phone attitude. Two independent methods of estimating the phone attitude are introduced.

2.1 Gyroscope
The MEMS gyroscope used in smartphones detects the 3-axis angular velocities of the phone motion. To derive the instant phone attitude, we need to perform continuous integration on the angular velocities. We deal with two coordinate systems in deriving the phone attitude. One is the earth coordinate system (we call “geo-frame”) and the other one is the phone body coordinate system (we call “body-frame”).

The goal is to get the phone attitude in the geo-frame, i.e., to calculate the relative difference between the body-frame and geo-frame. Figure 1 depicts the output of the MEMS gyroscope, which are the real-time 3-axis angular velocities ($\omega_x$, $\omega_y$, and $\omega_z$) around the Roll, Yaw, and Pitch axis in the phone body-frame. $X_e$ (pointing to the Earth east), $Y_e$ (pointing to the earth north) and $Z_e$ (parallel with the
Gravity (north) and compass are the three reference axes in the geo-frame. With continuous integration, the phone attitude can be calculated and represented as the relative difference of the two coordinate systems, which can be described by a rotation matrix, or the angles between the three supporting axes in the two frames, i.e., $\alpha$, $\beta$, and $\gamma$ (shown in Figure 1).

In order to accurately integrate the angular velocities, we apply the Euler Axis/Angle method to do the integration and tackle the problem from the perspective of the geo-frame, which is fixed during the phone motion. The method finds an equation of the rotation speed in the geo-frame based on differential. During the integration, the total phone motion time is divided into multiple time slots and the phone rotation is a sequential combination of the rotation within each slot.

**Performance Summary.** According to our experimental studies, the impact of different factors on MEMS gyroscope performance is summarized as follows.

- The tracking error accumulates as the time increases.
  - If the phone motion is within the dynamic range and sensor bandwidth, the gyroscope tracking result is accurate in a short time period. But the error can be big after a long time period (e.g., 10 mins) even when the motion frequency is low.

- The tracking error is highly related to the motions, i.e., the angular velocity and linear acceleration, and can be approximately estimated according to them. At the same time, the high frequency motion (i.e., the phone motion is out of the dynamic range) significantly pollutes the consequent attitude tracking result.

**2.2 Gravity and Compass**

The phone attitude also can be estimated using the gravity and compass sensor readings. As depicted in Figure 2, given the direction of gravity on the phone body-frame, the phone attitude is constrained on a conical surface in the geo-frame.

On the other hand, the compass outputs the angle $\delta$ between $Y'$ and $Y_e$ axis (pointing to the earth north) in the geo-frame, where $Y'$ is the projection of $Y$ axis of the body-frame on the $X_e$-$Y_e$ plane of the geo-frame. Considering the angle $\delta$ between $Y'$ and $Y_e$, we can thus uniquely fix the phone attitude on the conical surface. This provides us an alternative way to determine the phone attitude.

**Compared with gyroscope.** The attitude estimation from the compass and accelerometer is independent and of different nature compared with the result from the gyroscope. The compass and accelerometer give instant status estimation which is unrelated to any previous estimations, while the gyroscope gives a cumulative estimation of the attitude through continuous integration on angular velocities. Such different natures in their performance provide us the opportunity to complement the gyroscope estimation with calibration from the compass and accelerometer at “good” moments.

**3. OPPORTUNISTIC CALIBRATION**

We use an opportunistic calibration technique to identify “good” opportunities to calibrate the phone attitude. The basic idea is to leverage the gyroscope estimation to capture phone attitude dynamics. As our experiments reveal in §2.1, the gyroscope can provide very accurate attitude tracking in short time periods (e.g., within 10s). Although the instant attitude estimation of gyroscope may not be accurate due to base errors from previous states, the estimated attitude change is accurate for most of the time (when phone motion is within the safe range of the gyroscope), which sets a very good reference. We compare with the attitude change derived from the compass and gravity, and if both estimations derive the same change of phone attitude we believe the compass and gravity make an accurate attitude estimation. As the output of the compass and gravity is the instant attitude estimation, which is independent of previous states of the phone, we can then use it to reset the current attitude estimation and continue the gyroscope estimation from the new attitude base.
We incorporate the three IMU sensors and propose A³, an accurate and automatic attitude detector to continuously estimate the phone attitude. Figure 3 illustrates the A³ system architecture. There are two major components: gyroscope tracking and opportunistic calibration. As depicted in Figure 3 (left), A³ tracks the phone attitude using the gyroscope. The angular velocities are adaptively integrated to calculate the phone attitude (the rotation matrix $\mathbf{R}$). The tracking error of the gyroscope is carefully estimated based on the real time monitoring of the phone motion.

4. THE DEMONSTRATION

In this demo, we will show the basic performance of our algorithm under two experiment settings. We will show the performance comparison of different algorithms under various conditions, and introduce a mobile application that can benefit from accurate attitude estimation.

Performance comparison. In the demo, we will compare the performance of different algorithms for phone attitude estimation. As depicted in Figure 4, the user can use the phone in arbitrary ways. Different algorithms estimate the real-time phone attitude independently and their tracking results are displayed on 3 different screens. Users can examine the estimation result of individual axis, i.e., Roll, Yaw, and Pitch axis, separately, and also the overall phone attitude along the 3 axes. In the demo, we will also introduce some influences from the magnet and high frequency phone motion, etc., which may pollute the sensor output and may be harmful for the algorithms. Users can see the impact of the influences on different algorithms and compare their performance in tough environments.

Attitude-based applications. In the demo, we will also show the potential attitude based applications. Users can play a car driving game using smartphones. Two snapshots are shown in Figure 5. Figure 5(a) introduces the game settings. The smartphone is used as a controller, with which the player can change the gear, accelerate the car or make a brake. The target car and the driving environment are displayed on a PC or laptop screen. The phone attitude is used to make turns. As depicted in Figure 5(b), the player is using the phone attitude to make a left turn and accelerate the car at the same time.

Equipments and settings. In the demo, we will bring 3 laptops and 2 mobile phones by ourselves. Additionally, we need a table (around 1m×0.5m size), a board for the introduction poster (A0 size), and an electronic screen (around 25∼30inch) for the attitude-based games. Mobile phones use the WiFi network to transmit data to laptops. The setup time is about 10 minutes.

5. REFERENCES