Smartphone-Based Measurement of Acceleration: Development of a Smartphone Application for Use in an Engineering Dynamics Course

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Abstract

There is an increasing trend towards use of smartphones as mobile computing devices, and engineering education should stay abreast of this movement. The built-in sensing capabilities of most smartphones lend themselves especially well to engineering mechanics classes (such as Dynamics) in which kinematic relationships between position, velocity, acceleration, and time are taught. The purpose of this paper is to describe the development and implementation of a smartphone application and laboratory exercise to allow students to use smartphones to collect kinematic data during a routine activity (such as driving an automobile). The smartphone application, which obtains position and velocity data using a smartphone’s built-in assisted-global positioning system (A-GPS) and three components of acceleration using the built-in accelerometer, is made available to students. Following data collection, the laboratory exercise requires students to calculate and compare normal and tangential components of acceleration based on each of the two recorded data sets. In addition to introducing students to application development, the laboratory described here also provides an opportunity for deeper learning about computational methods (such as numerical differentiation) and approaches to dealing with noise in experimental data.

A sample data set is provided to demonstrate the calculations required to compare acceleration values measured using the on-board accelerometer with acceleration values calculated from position and velocity data collected using the on-board A-GPS. This laboratory was deployed in Fall 2013 and Spring 2014 semesters and, upon completion, a questionnaire was distributed to solicit student feedback on the laboratory exercise. Feedback suggests that students enjoyed using a smartphone application in a technical setting, appreciated collecting and analyzing data outside of an artificial laboratory setting, and felt that the laboratory contributed positively to their understanding of acceleration calculations in the normal-tangential coordinate system. The overall positive feedback supports the suitability of this laboratory exercise for implementation in a sophomore-level engineering dynamics course. Further, this laboratory exercise may be used as a strategy to address ABET student outcome (k), “an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.”

A copy of the laboratory handout and the Xcode project (source code for the smartphone application) used for the student laboratory exercise reported in this paper may be obtained by contacting the lead author.

Introduction

The use of mobile phones has grown considerably in the past decade. According to a June 2013 report published by the Center for Disease Control and Prevention, more than half of adults between the ages of 18 and 29 live in a household with only a wireless phone. Of those owning a wireless phone, 56% of all American adults have been shown to own smartphones. Increasingly, there is a trend towards smartphone use for mobile computing. The built-in sensing capabilities of most smartphone devices (including location, acceleration, microphone, and camera) allow for mobile sensing and communication capabilities that make smartphones particularly useful for engineers; however, smartphone-based sensing and application development are not typically included in most engineering curricula. Adoption of such devices may be further slowed by the fact that students may be uncomfortable using “emerging technology” that they haven’t encountered in the classroom.
The built-in sensing capabilities of most smartphones lend themselves especially well to engineering mechanics classes (such as Physics or Dynamics) in which kinematic relationships between position, velocity, acceleration, and time are taught. While traditional kinematics laboratory exercises have substantial hardware and software requirements including photo or video capture devices\textsuperscript{5-10} or accelerometers connected to data-logging devices\textsuperscript{11}, similar experiments could be conducted with only a smartphone.

The purpose of this communication is to describe the development and implementation of a laboratory exercise to allow students to (1) use smartphones to collect kinematic data during a routine activity (driving an automobile), and (2) compare acceleration values measured using the on-board accelerometer with acceleration values calculated from position and velocity data collected using the on-board assisted global positioning system (A-GPS).

Materials and Methods - Smartphone Application Development and Data Collection

The smartphone application was developed using the XCode 5 integrated development environment for Apple mobile devices. When the application is activated, the smartphone’s built-in A-GPS is used to obtain position and velocity data while the built-in accelerometer is used to obtain three components of acceleration. Data collection is synchronized and occurs at a rate of 1Hz (Table 1).

**Table 1**: Data values recorded by the smartphone application and their corresponding hardware sources.

<table>
<thead>
<tr>
<th>System Clock</th>
<th>A-GPS</th>
<th>Accelerometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Position (latitude, longitude, &amp; altitude)</td>
<td>Three components of acceleration (x, y, &amp; z)</td>
</tr>
<tr>
<td></td>
<td>Velocity</td>
<td></td>
</tr>
</tbody>
</table>

It is intended that the smartphone application should be used to collect kinematic data during the activity of driving an automobile. In order to use the application to collect kinematic information during driving, a phone must be placed on a flat surface in a vehicle so that the +y-axis of the phone points toward the front of the vehicle and the +z-axis of the phone points upward (Figure 1). In this orientation tangential acceleration of the vehicle is measured along the y-axis of the smartphone and normal acceleration is measured along the x-axis.
Data logging is initiated by pressing the “Log Data” button and a fixed number of data points are collected before the application composes an email with the data in comma-separated values (CSV) format (Figure 2). The data can easily be transferred from a smartphone to a computer for subsequent analysis.

**Figure 2**: At left, application interface during data collection. At right, email automatically composed by application with logged data in CSV format.

**Materials and Methods – Data Analysis**

The data collected using the application provides a means to calculate vehicle acceleration two different ways—one utilizing GPS location information and the other utilizing acceleration values reported by the
built-in accelerometer. For the case of a particle following a curvilinear path, normal and tangential coordinates are useful for describing the motion of the particle. Indeed, many mechanics textbooks use automobiles as a familiar and practical scenario to motivate the use of normal and tangential coordinates.\textsuperscript{13-15} In this case, the tangential basis vector can be thought of as being attached to the vehicle and pointing forward—always in the direction of motion. The normal basis vector can be thought of as being attached to the vehicle orthogonal to the tangential basis vector, always pointing inward to the center of curvature of the path. In this case, acceleration in the normal and tangential directions can be calculated entirely from GPS location data using Equations 1 and 2:

\[
a_t = \dot{v} \tag{1}
\]

\[
a_n = \frac{v^2}{\rho} \tag{2}
\]

where \(v\) is the velocity of the vehicle, \(\dot{v}\) is the time rate of change of velocity of vehicle, and \(\rho\) is the radius of curvature of the path. Calculation of \(\dot{v}\) and \(\rho\) requires numerical differentiation.

Based on the smartphone orientation in a moving vehicle (Figure 1), normal and tangential components of acceleration can also be taken as the x- and y-components of acceleration, respectively, reported by the built-in accelerometer.

**Materials and Methods – Analysis of Sample Data Set**

The following analysis is based on a sample data set collected by college sophomores using the smartphone application while driving the route shown in Figure 3.

![Figure 3: Driving route for which the sample data set was collected. The route is highlighted in red.](image)

Calculation of tangential acceleration from A-GPS data requires numerical differentiation of GPS-generated velocity data with respect to time according to Equation 1. The corresponding accelerometer-based acceleration value is the recorded y-component of acceleration. The tangential acceleration-versus-
time curves are shown in Figure 4. The correlation coefficient between GPS-based and accelerometer-based tangential acceleration values is \( r = 0.705 \).

![Figure 4](image_url)

**Figure 4**: Tangential acceleration as determined from accelerometer-based and GPS-based data

To facilitate calculation of normal acceleration from GPS data, latitude and longitude were converted to rectangular coordinates using the Haversine formula\(^{16}\). The first collected data point was designated as the origin and all distance calculations were referenced to that location. Changes in altitude along this route were small and were neglected in subsequent calculations. From the rectangular coordinate position data, the path’s radius of curvature was calculated according to Equation 3:

\[
\rho = \left| \left(1 + \left( \frac{dy}{dx} \right)^2 \right)^{3/2} \frac{d^2y}{dx^2} \right| 
\]  

(3)

where the first derivative \( \frac{dy}{dx} \) was calculated using the forward difference method according to Equation 4:

\[
\frac{dy}{dx} = \frac{y(x+h)-y(x)}{h} 
\]  

(4)

and the second derivative \( \frac{d^2y}{dx^2} \) was found by applying the forward difference method to the first derivative values. In general, error-checking must be performed to avoid division by zero errors in Equation 3. Normal acceleration based on GPS location and velocity data may be calculated for each data point using Equation 2 and compared to the corresponding component of acceleration (x-direction) recorded by the accelerometer. The resulting normal acceleration-versus-time curves are shown in Figure 5. The correlation coefficient between GPS-based and accelerometer-based normal acceleration values is \( r = 0.664 \).
Figure 5: Normal acceleration as determined from accelerometer-based and GPS-based data.

Discussion & Conclusions

Of the eleven “most important” concepts identified in the creation of the Dynamics Concept Inventory\(^\text{17}\), four deal purely with kinematic relationships. Kinematics receives similar attention on the Force Concept Inventory\(^\text{18}\). This focus on kinematic concepts seems appropriate as studies have shown that students struggle with kinematic concepts, particularly calculation of acceleration. For example, Reif and Allen found that undergraduate students and even course assistants in an introductory calculus-based physics course struggled to indicate correctly the acceleration vector of a swing at five different points on its swing path\(^\text{19}\).

The laboratory exercise presented here provides students with the opportunity to calculate the acceleration of a car during a driving activity in two different ways. Calculation of acceleration from both accelerometer-based data (a discrete, instantaneous measure acceleration) and GPS-based data (a measure of acceleration averaged over multiple time points) may help to reconcile common misunderstandings about instantaneous and average acceleration (Halloun et al. report that students often do not distinguish between average and instantaneous velocity\(^\text{20}\)). Indeed, the greatest contribution to the discrepancy observed between accelerometer-based and GPS-based acceleration data is likely due to average compared with instantaneous measurements of acceleration. Acceleration calculated from GPS data is necessarily averaged over several data points since velocity and radius of curvature calculations used in Equation 2 require multiple GPS location coordinates. GPS-based acceleration values hence represent an average acceleration over a finite time period and are representative of the general motion of the vehicle over that time period. Accelerometer-based acceleration values, on the other hand, represent a nearly-instantaneous reading. This instantaneous measurement of acceleration could easily be affected by a bump in the road or a sudden correction by the driver that is not representative of the general motion of the vehicle. Consequently, it might be most appropriate not to think of the GPS-based and accelerometer-based acceleration data as two curves that should ideally be identical, but rather as two sets of data that, when considered together, give a more complete picture of the motion of the vehicle.
Table 2: Student feedback on laboratory exercise.

<table>
<thead>
<tr>
<th>Question</th>
<th>Nothing</th>
<th>Little</th>
<th>A Bit</th>
<th>Some</th>
<th>Very Much</th>
</tr>
</thead>
<tbody>
<tr>
<td>How much did you learn from the laboratory activity?</td>
<td>1</td>
<td>3</td>
<td>11</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>How much did you learn from lecture and in-class examples?</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>How much did you learn by working assigned problems?</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td>How much do you think the lab helped you understand the concept?</td>
<td>0</td>
<td>3</td>
<td>17</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>What is the value of the lab compared with working additional example problems in class?</td>
<td>Very low</td>
<td>Low</td>
<td>Average</td>
<td>High</td>
<td>Very high</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>10</td>
<td>12</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>I find the concept</td>
<td>Very easy</td>
<td>Easy</td>
<td>Average</td>
<td>Difficult</td>
<td>Very difficult</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>6</td>
<td>22</td>
<td>9</td>
<td>0</td>
</tr>
</tbody>
</table>

A total of 37 students were surveyed in Fall 2013 and Spring 2014 on their experience with the laboratory exercise described here and the results are presented in Table 2. The results indicate that the majority of students felt that the laboratory exercise helped with their understanding of the normal-tangential coordinate system. When asked to complete the statement “One thing I liked about the lab was…”, specific student responses included:

- Learning to analyze information from real-world measurements
- Using software (Excel) to do calculations
- I liked how it related to class and expanded on things we learned
- Lab was applicable to situations everyone is familiar with
- The relationship to real-world applications
- I enjoyed using real-world data that we could gather ourselves again in the future
- Real-life relevance to concepts presented in class
- Real-world concept problems tend to help with understanding and reasoning
- Taking real-world data and generating other useful data is helpful to my learning style
- I like examples where I may apply for my own experiments
- Instructions were clear but still made me think things through
Interestingly, responses were mixed as to the value of the laboratory compared with working additional example problems in class. The median response to the question “What is the value of the lab compared with working additional example problems in class?” was “Average”. When asked to complete the statement “One thing I would change about the lab was…”, specific student responses included:

- Provide more information on how to do the calculations and what our curves should look like
- Provide a graph of what we are going for so we know if we are doing it right
- A little more clarity on what outcome/results are desired
- It wasn’t clear what the end result should have looked like
- I would like the class to deliberate about the findings

These statements together with informal polling suggest that students were not confident in their results and felt uncomfortable working on a problem that did not have a single “right answer.” This sentiment is similar to the unease often associated with working on open-ended problems.21, 22

While applications similar to the one developed for this laboratory exist and are available for download, the smartphone application presented here was intentionally left with only basic functionality to encourage students to begin learning about application development and to make modifications to the application code. Although modification of the application code was not required to complete the lab, the code was made available to interested students. Modifications that students have made to the application include incorporating user-selectable data collection frequency and duration. In addition to introducing students to application development, the laboratory described here also provides an opportunity for deeper learning about numerical methods and approaches to dealing with noise in experimental data sets (both the accelerometer-based and GPS-based acceleration values tend to be noisy, but for different reasons).

In conclusion, the development and implementation of a laboratory exercise to allow students to use smartphones to collect and analyze kinematic data is presented. The sample data and analysis demonstrate the suitability of this laboratory exercise for implementation in a sophomore-level engineering dynamics course and student feedback suggests that understanding of acceleration calculations in the normal-tangential coordinate system was improved.

Author’s Note

A copy of the laboratory handout and the Xcode project used for the student laboratory exercise reported in this paper may be obtained by contacting the lead author at: sbevill@coloradomesa.edu.
References