Design of a Handheld-based Motion Graphing Application for Physics Classes

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Abstract: The design of handheld-based applications for learning support remains open for interdisciplinary research. In particular, technologies such as object-tracking software and augmented reality visualization running on handheld devices need to be explored more. In this work, we discuss how we used such technologies to develop a handheld-based motion graphing application. We made design considerations based on previous work and design guidelines for developing educational software on handheld devices. We compare against the various tools for graphing displacement, velocity, and acceleration as functions of time. Based on this comparison, we discuss how our handheld application could be easier to use and more practical for classroom use. Finally, we discuss our implementation, and then suggest future evaluations and research directions.

Keywords: augmented reality, handheld devices, motion graphing, physics education

1. Introduction

Advances in handheld devices such as smartphones and tablet computers, together with better internet connectivity, have inspired new ideas on how technology can help support the learning process (Wong, 2015). Although there are still barriers and limitations to integrating handhelds to the classroom (Khaddage, et al., 2015), there are already many success stories of adopting handhelds to the classroom (Curtis, et al., 2002; Looi, et al., 2011; Parnell and Bartlett, 2012). In the Philippines, schools such as Miriam College High School have already adopted tablet computers for the use of students and teachers. We expect more schools in the Philippines to do the same and acquire tablet computers. As such, there is growing interest on how handhelds could be leveraged on in daily classroom activities. One of the main concerns is how handhelds could be used properly to transition from the occasional, supplemental use of computers for instruction to more frequent use, thereby making these devices an integral part of the curriculum (Barnes and Herring, 2012).

Aside from the use of handhelds as a tool for documentation in scientific inquiry (Looi, et al., 2011) and documentation of the progress of students (Parnell and Bartlett, 2012), handhelds can be used as tools for experimentation (Kuhn and Vogt, 2013). Although there are several works on the benefits of using handhelds as tools for sketching, mapping concepts, data collection, word processing, brainstorming, etc. (Curtis, et al., 2002), there is limited work on using handhelds for experimentation. Moreover, there is limited work reporting development in this area, especially those using emerging technologies such as object tracking and augmented reality. In augmented reality, virtual information is presented on the real environment as if it coexists with real objects (Santos, Luebke, et al., 2014). To achieve this effect, the handheld device must be able to track the locations of physical objects in the real world. Because we are dealing with emerging technology such as augmented reality, existing design guidelines for educational handheld-based applications may not be enough to arrive at usable systems (Gabbard and Swan, 2008).

In response, we base the design of our handheld-based motion graphing application on previous work and known design guidelines. We explain how the existing design guidelines apply to our application, as well as possible issues that are not covered by the existing guidelines. We also justify the benefits of our system over other methods of motion graphing. We argue that our system could be easier to use, thereby more practical for the classroom setting. We then discuss the

implementation of our system which uses readily accessible technology. We conducted a preliminary evaluation of this prototype and found possible improvements. Finally, we discuss how such a system can be used and evaluated in the classroom.

2. Related Work

Science experiments that "…(1) [were] designed with clear learning outcomes in mind, (2) [were] thoughtfully sequenced into the flow of classroom science instruction, (3) [were] designed to integrate learning of science content with learning about the processes of science, and (4) incorporate ongoing student reflection and discussion, …" improve not only student comprehension of the subject matter but also student's curiosity towards science and its reasoning styles (Singer, Hilton, and Schweingruber, 2006, 5). Such student-centered activities use discovery approaches of learning science and integrate metacognition. In this paper, we discuss the design of a handheld application that aims to support these discovery approaches. We explore some existing design guidelines for handheld tools for supporting learning. We then point to existing handheld-based systems for scientific learning, and explain the difference of these systems to our motion-graphing application. We provide an overview of motion graphing in physics education and provide our analysis of existing systems. Based on this analysis, we designed a handheld-based motion graphing application that could be easier to use in the classroom setting.

2.1 Designing for Handhelds

Handhelds have small screens which makes it difficult to show multiple workspaces (windows or panels) at the same time while maintaining overall usability. In response, Luchini, Quintana and Soloway (2004) summarized two general design principles for designing handheld applications based on a review of prior work and their experiences in working in this area. The first design guideline is *task-based workspaces*: developers should "support different component tasks of learning activity within individual workspaces that include the necessary scaffolds, information and tools. This task based decomposition preserves the conceptual integrity of the learning activity while allowing the salient component tasks to be usably supported within handheld screens" (p. 137). Unlike desktop-based applications that can support many components, handheld applications should be designed to support only one task. For example, a desktop application may have many components that support the whole scientific research process, whereas a handheld application should be designed for one specific task within the scientific research process (e.g. on-site data gathering). The second design guideline is *dual-purpose elements*: developers should "design interface elements to serve a dual role by providing both functionality and scaffolding. The use of such dual-purpose elements reduces the number of tools and scaffolds that must be included in an individual workspace and increases the usability of the handheld interface" (p. 137). For example, instead of showing a flowchart of a particular task within the scientific research process, a navigation menu can be used both as a functional menu and a flowchart designed as scaffold for students. By scaffold, we refer to the various supports that help students to mindfully engage in unfamiliar work (e.g. use a handheld device for on-site data gathering).

Aside from usability issues arising from the small screen and limited workspace of handheld devices, unconventional uses of handheld devices such as using it for object-tracking and augmented reality may lead to unique usability issues (Santos, Polvi, et al., 2014). Although augmented reality may be designed to be intuitive and ease cognitive load (Santos, Luebke, et al., 2014), there are limited usability evaluations for this emerging technology (Santos, Chen, et al., 2014). In particular, augmented reality and its enabling technology – object or scene tracking – is susceptible to perceptual and ergonomic issues. As such, we recommend developers to watch out for these issues and make sure that their three-dimensional visualizations are easy to understand, and that the device is easy to handle during the operation of the application.

One important factor that may affect the adoption of handheld-based applications is teacher readiness. In rural Georgia, USA, the lack of adequate faculty preparation contributed to the difficulty of transitioning to the use of handheld devices (Arnold, 2015). We anticipate the same

difficulties in the Philippines, not only in rural areas but also in the public schools found within cities. As such, we aim to implement a simple but flexible system that could be easily rolled out in schools, without the need for extensive training of teachers.

2.2 Handhelds for Scientific Inquiry and Experimentation

Looi, et al. (2011) developed a science curriculum for primary students that involve the use of handheld devices for mobile seamless learning. In their work, they asked the students to use handheld devices for note-taking, sketching, word processing, communicating, facilitating games, taking pictures, etc. as part of lessons conducted in collaboration with classmates and parents. Through their research, they have demonstrated the use of handheld devices in supporting mobile inquiry learning. Results of their evaluation show that they were able to encourage positive attitudes from students. Moreover, the students were able to achieve better learning outcomes. Similar to the work of Looi, et al. (2011), we aim to contribute to supporting science learning. However, instead of focusing on more conventional uses of handhelds like communication and documentation, we focus on unfamiliar usage of handheld devices such as motion capture. To achieve this kind of system, we need to use emerging technology like augmented reality, which may have different usability issues.

Aside from documentation, handhelds can be used for experiments in physics (Kuhn and Vogt, 2013). In their work, Kuhn and Vogt (2013) designed three student experiments that use handhelds. Two of the experiments use mobile phones that emit pure tones to measure acoustic beat and acceleration due to gravity. Another experiment is about using the camera of a cellphone to observe the infrared light emitted by remote controls. Kuhn and Vogt (2013) suggest creative uses of handhelds in physics experiments without requiring them to develop a special handheld-based application. They suggested the use of external sensors like microphones attached to a desktop computer, as well as the use of freely available software for desktops. Aside from the three individual experiments proposed by Kuhn and Vogt (2013), we think handhelds are also useful for graphing motion. Handhelds could be used in several experiments and activities in kinematics. To encourage the use of our system, we aim to make the setup and execution time quick and easy.

2.3 Motion Graphs in Physics Education

Motion graphs are graphical representations of the movement of an object through space and time. These representations can be used to emphasize the concepts of slope, and area of a graph (or the derivative and integral, for calculus-based physics classes). Three motion graphs are often used in physics discussions, namely, displacement vs. time, velocity vs. time and acceleration vs. time. The slope of the displacement vs. time graph gives the velocity of the object, whereas the slope of the velocity vs. time graph is the acceleration of the object. Hence, the displacement vs. time graph is essential because the velocity vs. time and acceleration vs. time graphs can be drawn from it.

A review by McDermott and Redish (1999) shows relevant physics education studies that enumerate student difficulties in understanding motion graphs, such as misinterpreting the graph's representation to the object's actual motion, and misreading the values of the quantities from the graphs. The recent study of Wemyss and van Kampen (2013) concludes that "...a correct qualitative understanding of a distance-time graph is not sufficient to correctly determine a value for the speed" (p. 1). In this regard, the use of technology in science instruction could bring increased student performance (Woodrow, Mayer-Smith, and Pedretti, 1996; Shieh, 2012). Technology in physics education can be found not only in graphing motion (Roschelle, Kaput and Stroup, 2000; Kuhn and Vogt, 2013) but also in electricity (Gutwill, Fredericksen, and White, 1999) and thermodynamics (Linn, Bell and Hsi, 1998), among others.

2.4 Systems for Motion Graphing

Plotting the motion of an object on a graph can be done in using several systems. We summarize the advantages and disadvantages that arise from the use these systems.

2.4.1 Ticker Timer

A ticker timer involves a mechanism that prints on a continuous paper (the "ticker tape") at a specific interval or frequency. For example, a ticker timer can be set to print 50 dots a second, or 50 Hz. The ticker tape is attached to an object such that as the object moves, it pulls the ticker tape out of the printer. For every second of the object's motion, 50 dots would have been printed on the ticker-tape. Figure 1 illustrates how a ticker-tape timer works.

The ticker tape is used to graph motion by cutting the ticker tape according to equal intervals of time which are represented by equal number of printed marks. In the previous example, the ticker tape may be cut to strips that contain six dots each. The strips are then placed on a velocity vs. time graph, with the time axis calibrated at 0.1 second intervals (since it takes a second for 50 dots to come out, it then takes 0.1 second for 5 dots to come out). The velocity axis is calibrated based on the lengths of the strip, since the velocity of the cart would be equal to the length of the strip divided by 0.1 s. Figure 2 shows a sample velocity vs. time graph using strips of ticker tape.
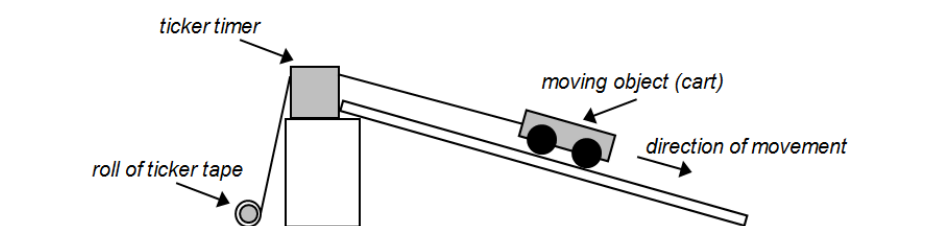

Figure 1: A sample setup which uses a ticker timer. A cart moving down the ramp pulls the ticker tape that is attached to it.
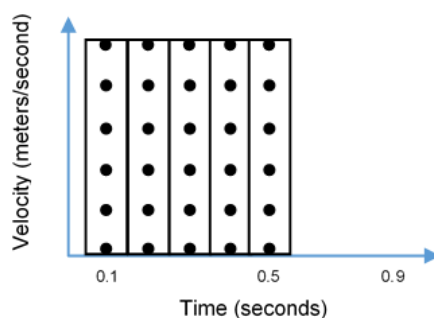

Figure 2: A sample velocity vs. time graph using strips of ticker tape. Note that the strips have the same number of dots on them and they are of the same length, which means that the object attached to the ticker tape is moving with a constant velocity.

One advantage of using this system is the cost. The timer is relatively cheap compared to other methods presented here. Teachers can also improvise on the ticker timers. Another advantage is that this system does not require a lot of technical knowledge to operate. However, paper jam is a common problem with this device because of its mechanical nature. Ensuring the correct frequency of the timer is also an issue, as this will bring inaccurate results. Furthermore, objects that initially move and then stay at rest cannot be properly registered by the ticker-tape. The span of time at which the object is at rest cannot be distinguished on the ticker-tape because the paper will also stop from coming out of the printer and the dots will overlap with each other. Lastly, movements going back to the direction of the printer cannot be registered because the paper can only be pulled in one direction.

2.4.2 Ultrasound Motion Sensor

One motion sensor that can be used to graph the movement of an object is PASCO's Motion Sensor. PASCO (www.pasco.com) manufactures computer-interfaced sensors bundled with software that

can be installed on electronic tablets and personal computers. PASCO's motion sensor uses ultrasound to indirectly measure the distance from the sensor to a target object. The system sends out pulses of ultrasonic waves which reflect off the target object and received back by the sensor. The software then analyzes both the roundtrip travel time of the pulse and the speed of sound in air to compute the distance of the object. The software also plots the distance vs. time graph of the object, the velocity vs. time, and acceleration vs. time graphs. The system allows the user input to change the sampling rate. Figure 3 shows how the PASCO Motion Sensor operates.

An advantage of this device is that it can measure the distance of objects as far as eight meters away with the object at least 15 centimeters away from the sensor. This range decreases as sampling rate increases. This feature for adjusting the sampling rate is also an advantage. Higher sampling rate produces more data points which can be processed by PASCO's software, or exported to third-party spreadsheet or data processing application. The primary disadvantage of using this device is its cost. In the Philippines, such dedicated systems may be considered impractical. Schools may only have a few of these PASCO setups, thus making difficult or impossible for a whole class of students to use it simultaneously. In addition to cost, another disadvantage of this system is its complexity. We think the setup and the software used for post-processing the data can be made simpler, thereby easier to use.
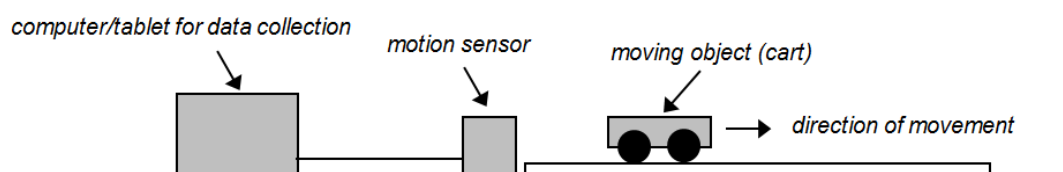

Figure 3: A setup for graphing motion using a motion sensor.

Table 1: Advantages and disadvantages of different motion graphing devices

	Ticker Timer	Motion Sensor	Video Logger
Advantages	• relatively cheap • low-technical knowledge required to operate	• can measure movement ups to eight meters • data can be exported to other programs	• covers many types of movement (projectile motion and circular motion) • can measure movement as long as the object is within the video frame • data can be exported to other programs
Disadvantages	• paper jam, mechanical issues • manual graph plotting • cannot properly register the span of time an object stopped, nor when objects move toward the ticker timer	• expensive • requires technical knowledge (interfacing, post-processing software)	• expensive • tedious marking of individual data points • requires technical knowledge (interfacing, post-processing software)

2.4.3 Video Logger

Vernier's Logger Pro (for desktops) and Video Physics (for tablets), and PASCO's Capstone can analyze recorded videos of moving objects for constructing motion graphs. Similar to PASCO,

Vernier (http://www.vernier.com/products/software/lp/) also manufactures computer-interfaced sensors partnered with software.

Generally, video logging systems have four phases of operation. The first phase is to import a video of the object for analysis. The second phase requires the user to place "markers" on the object per frame of the video. The user identifies where the object is and places a mark on it. The desktop application then overlays this mark on the frame. The software advances the video to the next frame and the user marks the object again. This process is repeated until the end of the video clip. The third phase is calibrating the video. The user can set the point of reference (or the zero-meter mark), and the scale that the software will use to measure the distance between the marks on the object. This is done by having a meterstick (or other objects with known lengths) recorded within the video frame. The last phase is when the software plots the motion graphs.

An advantage of this method is that it can analyze motion in two-dimensions, such as the movement of a projectile and circular motion. However, the tediousness of the marking phase is a disadvantage. If a video that lasts 3 seconds is recorded at 50 frames per second, the user has to make 150 marks on the object. Rather than manually tracking the object, we propose in our work to automate this process by applying existing augmented reality software that includes object tracking.

Table 1 summarizes the advantages and disadvantages of existing methods for motion graphing. Based on this analysis, we formulated our design goals listed in Section 3.

3. Design Goals and Research Questions

We have the following design goals for our handheld-based motion graphing software:

- *Task-based Workspaces* – because the screen is small, we need to focus on using the application for one specific task only.
- *Dual-purpose Elements* – to maximize the small workspace and two help the students operate the application, we must provide both function and scaffolding with our interface elements.
- *Comprehensibility* – we should make the augmented reality visualization easy to understand by designing against perceptual issues of handheld augmented reality.
- *Manipulability* – The device should be easy to handle during the operation of the system.
- *Low Training Needs* – the application should not require much training of teachers.
- *Time Saving* – as much as possible, time should be saved in setting up the system, executing the experiment and post-processing the data.
- *Cost Effective* – as much as possible, we should use readily accessible devices and software so that schools can adopt them easily.

Through this ongoing research, we aim to explore the following research questions:

- Can augmented reality technology be used for a handheld-based motion graphing application?
- What considerations must be made to design this application?
- What features of this application make it more useful in physics experiments than the existing methods of graphing motion?
- What are the measurable benefits of using this application to the learning process?

4. The Proposed System

We discuss a sample use case, implementation and preliminary evaluation of our proposed system.

4.1 Sample Classroom Discussion on Motion Graphs

A class discussion involving graphing motion aims to teach students how to draw and analyze the three motion graphs. The analysis includes using the slope and/or area under the graphs. Typical questions ask students to identify instances when the object is speeding up, slowing down, moving

with a constant velocity, moving away from the origin, or compute the total distance travelled by the object, or its displacement from the origin. A lesson in graphing motion in a physics class may ask students to plot the graph of the following scenario:

"A fashion model's coach is a hard-core physicist by heart. The coach gave the model the following set of instructions: 'From the back, which is the starting point, walk 3 meters up front in 5 seconds. Then, stay there for 5 seconds. Run fashionably for another 5 meters in just 2 seconds. Stop and pose for your final exposure for 5 seconds until the curtain closes."

Manually graphing the movement of the fashion model will show the following displacement vs. time, velocity vs. time and acceleration vs. time graphs, as shown by Figure 4.

This lesson can be enhanced with technology. Students can be asked to act as fashion models and perform the set of movements in front of a motion sensor. The use of the sensor requires the student to hold a cardboard or any surface that can reflect as much ultrasound back to the sensor as possible. This setup is shown in Figure 5. Similarly, the students may record their movements on a video. The video is then imported to any video logger software in Section 2.4.2. Using the ticker timer in this lesson is not ideal because the fashion model will have to stop twice. As pointed out earlier, a ticker timer cannot properly register the amount of time a target object is at rest.
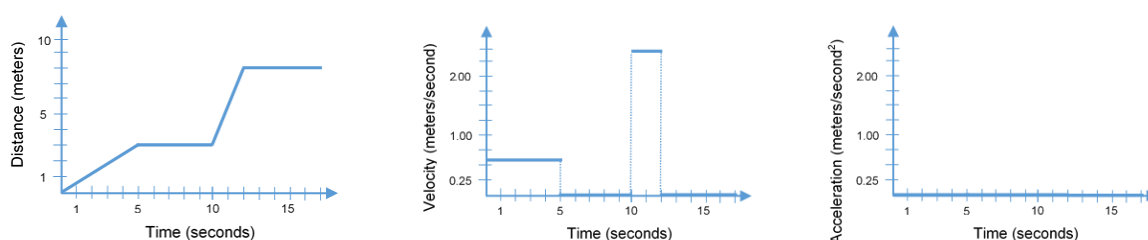

Figure 4: The motion graphs of the fashion model as plotted manually: (from left to right) distance vs. time, velocity vs. time and acceleration vs. time.

Figure 5: Two students from Miriam College High School perform the set of instructions for the fashion model scenario. A PASCO Motion Sensor is located in front of the student holding a black cardboard. Meter sticks are set on the floor to guide the student's movement. A second student manages the sensor. She also collects the data from the sensor using a tablet computer.

Our proposed system shown in Figure 6 and discussed in Section 4.2 aims to support this use case. The software must be able to measure the distance between an object and a reference point in a given time interval. By having the software take note of the distance travelled by the object at a specific time, a distance vs. time graph can be constructed, from which both velocity vs. time and acceleration vs. time graphs can be drawn.
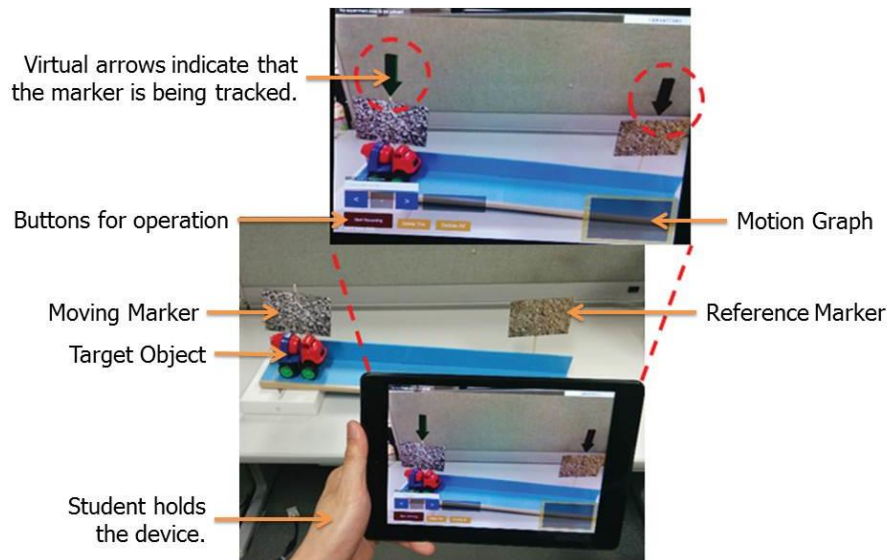
Figure 6: The current implementation of the system.

4.2 Implementation

Figure 6 shows the current implementation of our proposed system. The main operation of the device is as follows: The workspace is a camera view of the scene with a few buttons for operation and a small window at the lower right, to quickly show the graph. The students point the device to markers, then virtual arrows appear to give feedback that the application is tracking. The students simply press the "Start" and "Stop" buttons to capture the movement of the target object. The generated motion graph will be shown at the lower right. If the graph looks incorrect, the student can simply discard the data. If the graph looks correct, they can send it to online database to view the graph in a bigger screen. Students can also download their raw data from the website for further processing. They can also access their data at home for making reports.

Our motion graphing application caters to both Android and iOS handheld devices with a supporting web service and web application. There are three main components: the mobile component, the server component and the web component.

4.2.1 Mobile Component

We use the game development environment called Unity (https://unity3d.com) to develop for both Android and iOS devices. Our mobile component contains several subcomponents including tracking, graphing, database, calculator and networking. The most important subcomponent is the tracking part, which we accomplished using the marker-based tracking technology of Vuforia (https://developer.vuforia.com).

4.2.2 Server Component and Web Component

We prepared a server database to manage the students' experiment data. As such, we implemented a server component to facilitate communication between the database and the handheld application, and between the database and our web application. The web component handles getting the data from the server database, and showing larger motion graphs on a desktop computer.

4.3 Initial Deployment and Testing

We are currently improving the prototype based on initial input and testing from 11 students and two physics teachers of Miriam College High School in Metro Manila, the Philippines. The teachers

were able to successfully install the application in Samsung 10.1, 16 GB, Android tablet computers. These tablets are available to the students of the said high school in a 1:1 ratio. Thus, both individual and group explorations are possible.

Given the first prototype, suggestions for improvement were raised from both teachers and students. Suggestions include having an adjustable sampling rate to make the application more flexible to the user's specifications. Currently, motion sensors such as the PASCO Motion Sensor allow for inputs of the sampling rate. Another suggestion is to set the markers such that they are initially close together which corresponds to zero-separation distance. The application will be more intuitive if the markers would follow the same convention of the Cartesian coordinate system, where left and down are negative directions, and right and up are positive. Lastly, students initially thought that the virtual arrows were forces acting on the target object. To avoid this confusion, we plan to replace the arrow with a different symbol.

5. Conclusion and Future Work

In this paper, we discuss our design of a handheld-based motion graphing application for use in physics classes. We draw design requirements from previous work and design guidelines. We also made considerations from the perspective of Philippine education and women's education. We presented different methods of graphing motion in physics classes, including the benefits that they provide, and their limitations. We then described our prototype and the initial feedback from teachers and students.

After we develop an acceptable version of the application, we will evaluate it based on three constructs – usability, interaction and learning outcomes. The evaluation will be conducted following a quasi-experimental method, with a pre- and post-test research design for the learning outcomes. Three groups of students will serve as respondents of the study. The first group will follow a traditional mode of studying motion graphs without the use of any technology. The second group will use PASCO Motion Sensors, while the third group will use our handheld-based motion graphing application. The results of the pre- and post-tests will help quantify learning outcomes.

Usability may be measured by observing the behavior of the three groups. The group which takes a shorter time in setting up their devices and experiments, and also a shorter time in gathering data and analyzing data will reveal the method that is easier to use. Additionally, the length of the laboratory handout which enumerates the steps of an experiment can also be an indicator of a device's ease of use. The handout will be written by teachers who are not aware of this study to remove bias. The frequency of student questions that relate to the use of the device to teachers also indicate ease of use. The fewer questions indicate that the interface is intuitive. Respondents from the second and third groups will also fill up questionnaires. Results of this survey will be used to further gauge how students find the usability of the software.

Classroom dynamics might also be affected with the introduction of the handheld-based application. How the software facilitates collaborative learning can be measured through behavior observation and questionnaires. The groups will be observed to see whether the software encourages more student-to-student interaction and greater participation in pre-lab, actual lab, and post-lab phases of the class discussion.

Acknowledgements

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