AC 2011-2168: OH, G! HIGH SCHOOL STUDENTS DISCOVER GRAVI-TATIONAL ACCELERATION USING UBIQUITOUS TECHNOLOGY

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Abstract

Digital cameras became commercially available in the early 1990s and have since seen a rapid increase in capability while exploding in popularity. Most digital cameras provide for the collection of digital video at a rate of 30 frames per second, and a new series of inexpensive cameras that can collect at much higher frame rates are beginning to hit the market. The video capabilities of these cameras provide an effective method of acquiring position versus time data. Louisiana Tech University has partnered with three high schools in our region to develop a project-based physics curriculum. One module of the curriculum involves an empirical analysis of falling body data to estimate the local gravitational acceleration. The project is designed so that high school students collect video footage of the object against the backdrop of a length scale. Students advance the video one frame at a time to associate position and time. This data is studied using the basic definitions of velocity and acceleration and finite difference techniques to determine velocity as a function of position, eventually leading to the gravitational acceleration (g). The same sort of analysis is used later in the course module for projectile motion, resulting in the progressive development of student competence in collecting and analyzing this data. High speed video is collected in a number of other cases and added to the curriculum materials to illustrate time dependent phenomena, such as material deformation, waves, pendulum motion and stick-slip friction. The paper provides clear examples of K-12 projects that utilize digital cameras for data acquisition as well as assessment data regarding the experiences of high school teachers and students who utilize the technology.

Introduction

Engineering educators who are concerned with the future needs of the engineering profession have realized for a long time that a hands-on, project-based approach fosters the development of students who are confident in their ability to accomplish real achievements with their learning¹. The project-based curriculum revolution was born in the 1990s in the United States; with the key driving force arising from the National Science Foundation Engineering Education Coalitions²⁻⁵.

Collecting and analyzing data in the classroom is a way for students to discover truths on their own. Tools such as National Instrument's data acquisition devices can be used to collect data in the classroom, but even simpler devices can also be used to collect data. Over the past decade there has been much advancement in consumer digital cameras. Digital cameras are primarily used for taking pictures and videos for personal use. However, digital cameras can also be used as data acquisition devices. Recent publications have shown that low-cost digital cameras can be used in K-12 schools as teaching tools. Most approaches use digital photography only as a tool for documenting student work⁶. As another application, time-lapse photography can document changes that happen over long periods of time⁷. Additionally, digital cameras have been used to show more advanced concepts such as digital filtering and image processing⁸.

Most digital cameras also have the capability to capture video. With video capability, one can analyze and collect data to study an event that happens very quickly. Several software packages are designed to process video files to extract data regarding recorded events. A large body of literature describes the experiences of bringing these technologies into the K-12 classroom⁹⁻¹⁵. Video capture is very beneficial for analyzing time-dependent events in the classroom; however, the technology platforms (high speed hardware and/or commercial software) can be cost prohibitive for many schools. Alternatively, consumer-grade low-cost digital cameras have video modes that can effectively acquire position versus time data. These standard digital cameras typically record video at rates of 30 frames per second (fps), although other frame rates are also frequently available. Hands-on projects that demonstrate many K-12 fundamental concepts can be sufficiently modeled using data extracted from video shot at 30fps. It is critical to note that 30fps digital cameras are not capable of capturing events that are too rapid to be observed by the human eye. As a larger number of high frame rate consumer grade cameras become available, faster events can be captured in the classroom at a cost that is reasonable for many school systems.

Louisiana Tech University has partnered with high schools in our region to pilot our projectbased physics program. Hands-on projects in this program use low-cost digital cameras and free video processing software in the classroom as a way of gathering empirical data about moving objects.

Example Application: Falling Objects

This section provides a detailed example of how a digital camera can be utilized to acquire position versus time data for a falling body and how the data can be analyzed to determine the local gravitational acceleration ($g \approx 9.81 \text{ m/s}^2$). The module is designed to be suitable for high school students taking an engineering, physics, or mathematics course. The aim in this module is for students to build competence in using technology while discovering important fundamental physics concepts on their own. Other modules in the curriculum that employ video capture as a data acquisition tool are: material deformation, waves, projectile motion, pendulum motion, and stick-slip friction. These modules seek to employ an inductive learning approach were students utilize observation (video footage) along with simple engineering analysis and estimation to arrive at fundamental concepts.

The module presented here is written as it would be communicated to a student with the hope that others will be able to more easily adopt and adapt the module for their own use. The module shown is broken into seven sections:

- 1. Project introduction
- 2. Capture of video footage
- 3. Extraction of time and position from video data
- 4. Position versus time
- 5. Velocity versus time
- 6. Acceleration versus time
- 7. Data smoothing and g

Each of these sections is detailed below. Comments and assessment of student learning is provided in subsequent sections.

1. Project Introduction

You may have heard that Isaac Newton "discovered" gravity. What he really did was describe the effect of gravity using mathematics. (It would be hard to imagine that the earliest humans didn't know that things fell when they dropped them, so in a sense even they had discovered gravity.)

Today we have tools available to us that Newton did not have in his time. These tools make it much easier for us to discover the mathematics behind the tendency of objects to fall. In the experiment we begin today, we will be taking video of objects falling. The video we take can be analyzed to determine how the objects move once dropped.

2. Capture of Video Footage

- A. Determine the height from which you will be dropping your object(s). Our trials show that eight feet is adequate.
- B. Prepare a long paper "ruler" as the backdrop of the video you will take. The sheet should be the same length as the height from which you will drop the object. Use large, thick numbers so the scale will be clearly visible in the video (see Figure 1).



Figure 1 – Length Scale

- C. Attach the paper ruler to a wall in a place where a camera can be set up on a tripod (or held by hand) to take video of the falling object.
- D. When the camera is set up, try to just fit the full length of the ruler within the frame. The better lighting you get, the less blurry your object will look.
- E. Take a video of the object(s) being dropped the full length of the paper ruler, holding the camera as steadily as possible. Download the video footage to a computer for analysis.

3. Extraction of Time and Position from Video Data

The video should be opened in a video viewer of some kind on your computer. We used a free video utility called VirtualDub (<u>www.virtualdub.org/</u>) because it tells you the time associated with each frame to thousandths of seconds. The viewer should have the ability to step through the video frame by frame (this is sometimes done by clicking the progress bar at the bottom and using the arrow keys on the keyboard). You should also have a spreadsheet file open where you can begin recording data from the video, as in Figure 2.

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Figure 2 - Screen capture showing data extraction

For each frame, record a frame number, the time associated with that frame and your best estimate of the location of the falling object against the backdrop. Notice from Figure 2 that the frame number and time are near the lower right, and this data is directly entered into the spreadsheet (frame=34, time=1.133 s, distance=115cm). The frame can then be advanced to extract the next data point. Notice that this camera operates at 30 frames per second such that data points are separated by 1/30 second increments.

4. Position Versus Time

Figure 3 shows a plot of the position versus time data that we extracted from the video footage. A useful tool that can be used in data analysis is curve fitting which allows us to determine mathematical relationships that "best" fit our data. Most spreadsheet software packages have

built-in curve fitting tools. The equation shown in Figure 3 represents a mathematical relationship between the height of the object and the time. Thus, if we were to rewrite the equation with meaningful variables and units, we would have:

$$\mathbf{h} = \left(-488.46\frac{em}{s^{1}}\right) \cdot \mathbf{t}^{2} + \left(452.14\frac{em}{s}\right) \cdot \mathbf{t} + 229.35 \,\mathrm{cm} \quad (1)$$

The units in this equation were determined by making the coefficients cancel out the units of the dependent variable, time (t), while including the necessary unit for the dependent variable, height (h).



Figure 3 - Plot of position versus time showing best fit curve

5. Velocity Versus Time

When you drive, you can determine your average speed by dividing the distance you have traveled by the time it took you to travel it. Velocity is just like speed, except velocity implies that you are also interested in the direction of motion.

Average velocity is different from velocity because average velocity is measured over a non-zero amount of time, while velocity is an instantaneous quantity. For the falling object, we can determine the average velocity between successive frames by determining how far it moved and dividing this distance by the amount of time between frames, as in Figure 4.



Figure 4 – Extending results to determine average velocity versus time

Look closely at the data points on this plot in Figure 4. You may notice that the points are not in a perfectly straight line. What should our interpretation be for the "roughness" in the data? Do you think this is an accurate reflection of the actual velocity changes versus time, or is the actual velocity profile more smooth? If the actual change in velocity versus time was smooth, then where did the roughness in the plot come from?

Every measurement we take contains a certain level of error. There is no such thing as a perfectly accurate measurement. The measurements that we took by looking at the video were not incredibly accurate. Issues such as the blur of the object, the distance between the object and the backdrop (causing parallax), human error in identifying the location of the object, etc. reduce the accuracy of our measurements. The line that is fitted to the data is a tool we can use to ignore minor local variations and errors. The line instead focuses on the overall trend of the data. The equation shown on the graph can be interpreted in much the same manner as the equation we looked at for height versus time.

$$v = \left(-972.95\frac{cm}{s^3}\right) \cdot t + 464.04\frac{cm}{s} \quad (2)$$

What could be done to make our measurements more accurate? Some ideas:

- Higher video resolution (number of pixels comprising each frame).
- More markings closer together on our backdrop. (There is a limit to this because you cannot make them too close together before you can't see them anymore in the video. This is related to the video resolution mentioned above.)
- Faster camera shutter speed (period of time over which light is collected to make a frame). This will make the object look less blurry.

• More precise image processing. There are more sophisticated methods to determining the location of the object in the frame than visual estimation. This may involve counting pixels.

6. Acceleration Versus Time

Remember that we have defined average velocity as a change in position divided by a change in time. Anyone who has been in a race knows what velocity is intuitively. You are trying to cover a specified distance in as little time as possible; a longer distance or a shorter time both mean you are going faster. Velocity is the rate of change of position, but is there a way that you have experienced a rate of change of velocity? Imagine sitting at a traffic light. When it turns green, you start driving, and in 5 seconds you are going 30mph. Your change in speed was 30mph, and the associated change in time was 5 seconds. The rate of change of your velocity, then, is

$$\frac{30mi/hr}{5s} = \frac{30}{5} \frac{mi}{s \cdot hr} \frac{5180ft}{mi} \frac{hr}{60min} \frac{min}{60s} = 88 \frac{ft}{s^2}.$$

This rate of change of velocity is called <u>acceleration</u>.

The units of acceleration can be confusing at first. What does it mean to have feet per second squared? Well, velocity can be measured in length per time (e.g. ft/s). These are the units in the numerator (the top part) of the acceleration fraction (velocity). The denominator of the acceleration fraction has the units of time, thus the units of acceleration can be thought of as Liengetal little mean convenient to recommon this function to [liength]

 $\frac{\boxed{[time]}}{[time]}$ but it is a little more convenient to rearrange this fraction to $\frac{\boxed{[tength]}}{[time]^3}$.

Recall Figure 4 where we plotted the average velocity point by point for the falling object. When we did this, the points were arranged more or less in a sloping line. We calculated the velocity at each point by dividing the change in position by the change in time. We can use the same method here to determine the average acceleration of the falling object between successive video frames. We can determine the change in velocity by subtracting the velocity in one frame from the velocity in the previous frame, and we can determine the change in time the same way we did before, as in Figure 5.



Figure 5 – Computing acceleration versus time from the velocity data

What does a graph like Figure 5 tell you? If you are thinking "not much" then you are right. This plot shows very little correlation between the quantities plotted. The problem with the method that we have used to find acceleration is that we are using data that has error to perform calculations. The plot of height versus time looks smooth because the error associated with each point is fairly small. The velocity versus time data looks rougher because the small height and time errors in the original data are magnified when we calculate velocity. By the time we calculate acceleration, we have magnified the error so much that the graph looks really messy. We don't really think that the acceleration of the falling object fluctuates this wildly, so we suspect that we have problems with measurement error.

The method that we used to calculate acceleration is a sound one, with one exception. The original data that we used had error built into it that became amplified in the process of doing our calculations. If we can get rid of (or greatly reduce) the error in the data we use, we can still find and plot the acceleration of the falling object versus time.

7. Data Smoothing and g

Figure 5 showed how performing calculations on data can cause error to compound and amplify. As we stack one manipulation on top of another, the error can grow to the point where it makes the manipulated data unusable. We need less error in our initial data so that our manipulations are useful.

Utilizing the "best fit" curves for position in Equation (1) and velocity in Equation (2) allows us to create a smooth curve that can eliminate some of the error from our data that arose out of our inability to find the exact location of the falling object in each frame. Plugging the time values from the video footage into Equations (1) and (2) lead to the corrected position and velocity values shown in Figure 6, respectively. The corrected velocities can then be used to compute corrected accelerations.

Frame	Time (s)	Measured Height (cm)	Corrected Height (cm)	Uncorrected Velocity (cm/s)	Corrected Velocity (cm/s)	Uncorrected Acceleration (cm/s²)	Corrected Acceleration (cm/s²)		Avera 0 -	ge Accele	ration +	vs. Tin	ne +
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33	1.100	136	135.67	-606.1	-606.4	-1431	-992		2000				
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37	1.233	44	44.24	-727.3	-736.3	0	-977				Time (s)		
38	1.267	18	18.09	-764.7	-769.0	-1101	-963						

Figure 6 – Data corrected using the curve fits from Equations (1) and (2)

What does the plot we have developed for acceleration versus time tell us? A line fit through the corrected acceleration data is horizontal (slope of zero). This means that the acceleration is not dependent on time, it remains constant. The analysis shows that the average acceleration is

$$a = 0 \cdot t - 976.9 \frac{cm}{s^2}$$
$$= -976.9 \frac{cm}{s^2}$$
$$= -9.769 \frac{cm}{s^2}$$

If the entire experiment is repeated for objects with different weights, we find that the acceleration value does not change very much as long as the ratio of the weight of the object to its cross-sectional area remains fairly large (this makes air resistance a minimal factor). Scientists have done repeated experiments with better equipment than ours, where the falling object falls in a vacuum. The average acceleration of objects due to earth's gravity at sea level has been determined to be $-9.81\frac{M}{s!}$ which is very close to what we have determined with our digital camera setup! The letter g is often assigned to the acceleration due to gravity.

Assessment of Student and Teacher Attitudes

The "falling object" module was designed to be completed in 4 class periods that are 50 minutes each. When designing the individual lessons, we were conscious of the possibility that students could lose site of the bigger picture and get lost in the details. Homework assignments were

designed to provide continuity between topics and to make sure that fundamental concepts (position, velocity, acceleration) were understood.

Sixteen students and their teacher were surveyed to determine attitudes regarding the use of digital cameras to acquire position versus time data in order to determine the gravitational acceleration. The results of the student survey are provided in Table 1, with a score of 1 representing strongly disagreeing and a score of 5 signifying strongly agreeing. The survey results are all above 4.00 except for the last question. Interestingly, the students will be required to complete another digital camera exercise within a month where they capture position versus time data for 2D projectile motion. It will be important for us to check again to see if their desire to use a digital camera for data acquisition has changed. We expect that this lower score is due to a lack of confidence, so it is anticipated that as confidence grows with repeated use, this score may rise. The survey shows that the students were impressed with the capability of the digital camera to capture the needed data with scores of 4.75 on the digital camera being a "powerful tool" and 4.81 on the importance of the digital camera for "gathering the data needed."

	strongly disagree 1	somewhat disagree 2	neutral 3	somewhat agree 4	strongly agree 5	mean
This project has given me a better understanding of how Earth's gravitational acceleration can be measured.	0	1	2	8	5	4.06
I believe that a digital camera is a powerful tool for data acquisition.	0	0	0	4	12	4.75
I now feel confident about making measurement estimates needed for this project using still frames from video.	0	0	0	7	9	4.56
This project has given me a better understanding of how everyday tools, such as a digital camera, can be used to collect data about things we observe.	0	0	4	4	8	4.25
I could not have gathered the data I needed for this project as successfully without the digital camera.	0	0	0	3	13	4.81
I would like to try measuring other things using a digital camera.	0	1	9	2	4	3.56

 Table 1 – Results of student surveys

Some student comments include:

- I liked being able to use frames to extract accurate information . . . that was pretty cool
- I enjoyed the Virtual-Dub program and being able to figure it out before others in my group
- The high speed / slowing of the video was interesting . . . the software was not so impressive
- Watching my partner's hand move in slow motion . . .
- The experiment uses a hands-on approach to gravity. You get to see each distance the ball travels using new technology that we are unfamiliar with

The teacher of the class also completed a survey that indicated she had positive feelings regarding the module. She commented, "I love that students determined acceleration due to gravity instead of just giving them another number to memorize – great way to derive the value!"

Planned changes to the module include providing more guidance / training for the teachers in the use of digital cameras to collect video.

Conclusions

Most low cost, digital cameras on the market today allow for the collection of video and have sufficient capability to capture accurate position versus time data. Coupling these widely available and easy-to-use cameras with free video editing software provides a method of data acquisition that has a very low entry barrier. That is, almost anyone in a modern society has access to the required hardware and software, and with a few training tips, can figure out how to acquire data useful for illustrating STEM principles. This paper illustrated the use of a digital camera to acquire the data needed to estimate the local gravitational acceleration; the module was presented in a way to allow other STEM professionals to adopt / adapt the content to suit their purposes. Assessment data shows a very positive impression of the application of this technology to STEM education.

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