The Maiden Voyage of a Kinematics Robot

Matthew L. Greenwolfe, Cary Academy, Cary, NC 27705 (March 2014)
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Introduction

In a Montessori pre-school classroom, students work independently on tasks that absorb their attention in part because the apparatus are carefully designed to make mistakes directly observable and limit exploration to one aspect or dimension. Control of error inheres in the apparatus itself, so that teacher intervention can be minimal.[1] Inspired by this example, I created a robotic kinematics apparatus that also shapes the inquiry experience. Students program the robot by drawing kinematic graphs on a computer and then observe its motion. Exploration is at once limited to constant velocity and constant acceleration motion, yet open to complex multi-segment examples difficult to achieve in the lab in other ways. The robot precisely and reliably produces the motion described by the students' graphs, so that the apparatus itself provides immediate visual feedback about whether their understanding is correct as they are free to explore within the proscribed limits. In particular, the kinematic robot enables hands-on study of multi-segment constant velocity situations, which lays a far stronger foundation for the study of accelerated motion. When correction is anonymous - just between one group of lab partners and their robot - students using the kinematic robot tend to flow right back to work because they view the correction as an integral part of the inquiry learning process. By contrast, when correction occurs by the teacher and/or in public (e.g. returning a graded assignment or pointing out student misconceptions during class), students all too often treat the event as the endpoint to inquiry. Furthermore, quantitative evidence shows a large gain from pre-test to post-test scores using the Test of Understanding Graphs in Kinematics (TUG-K).[2]

Background

As has been well documented in the literature, students encounter difficulties overcoming preconceived notions to understand kinematics.[2,3,4,5] Active learning or guided inquiry approaches have been shown to help address the problem.[6,7,8] In particular, Rosenquist and McDermott note that "instruction based on observation of actual motion can help students" understand kinematics.[9] Existing equipment in the lab allows the study of limited examples of constant velocity and constant acceleration motion, for example using constant velocity buggies, Atwood's machines or inclined planes. Meter sticks, stopwatches, video analysis, and computer-integrated sensors such as motion detectors allow the measurement of motion, and inquiry-based activities using them are common in physics classrooms.[10,11] With the kinematics robot, students can not only perform all the observational studies accessible with other apparatus, they can attempt to create a motion by describing it with their graphical and mathematical representations. Rosenquist and McDermott[5] also note the value of "producing a motion from the graph." The kinematic robot allows "translating back and forth between a motion and its graphical representations" to occur seamlessly throughout the curriculum, and with a greater variety of more sophisticated examples. Students thus have control of the complete learning cycle, opening up greater avenues for their own inquiry.

Lab work can also be supplemented by programs that display graphs alongside an animated figure,[12] but in Beichner's study of video analysis,[11] he cautions that "hands on involvement appeared to play a critical role," and recommends that computer visualization be combined with actual lab work. Laverty and Kortemeyer[13] note that computer-graded graphical kinematics problems add value to instruction, but "do not lend themselves to error analysis" because students "seem more likely to just try making a small adjustment to the graph they already tried instead of trying to understand the difference between their submissions, and why one of them is right, but the other is not." In a more recent study similar to the current work, Mitnik and collaborators[14] attempted to bridge the gap between computer simulation and hands on lab work by programming robots for their students to observe and measure, noting the approach was "novel [in departing] from the traditional approach of using robots just to teach Robotics related subjects ... the robot is not the aim of the activity, but just a means to help students understand other, non-robotic subjects." They also note increased motivation and engagement and better post-instruction test scores compared with a control group using just computer simulation. The current study goes a step further by enabling the students to program the robot themselves, so that the ultimate arbiter of correctness is the motion of an actual object, often observation of two robots running side-by-side to see if the motions match. By tying the graph drawn on the computer to the hands on lab work in the most direct fashion, the kinematic robots engage students and motivate them to work for mastery rather than just produce a correct answer.

How it Works

Students connect a Scribbler II robot from Parallax, Inc[15] to a computer by means of a serial port to USB adapter and a USB cable (illustration 1). On the computer, they use a graphical user interface to draw a kinematic graph - position vs. time, velocity vs. time or acceleration vs. time - and send it to the robot (illustrations 2 and 3). The information from the graph is saved in the robot's memory in the form of a program. The robot can now be disconnected from the computer and performs the requested motion when its start button is pressed. Velocity vs. time graphs can include any number of linear segments, created by clicking on the 'add segment' button, then dragging the end points or entering precise values. Discontinuities are not allowed in the graph. Instead, a very steep (but not completely vertical) segment can be used to program rapid transitions from one velocity to another or to give the robot an initial velocity. The acceleration vs. time graph can be any number of horizontal segments, and the position graph can be any number of linear segments or quadratic curves that are created simply by dragging the midpoint of a segment. The robot can also be programmed to turn between segments of motion to follow a two-dimensional path.

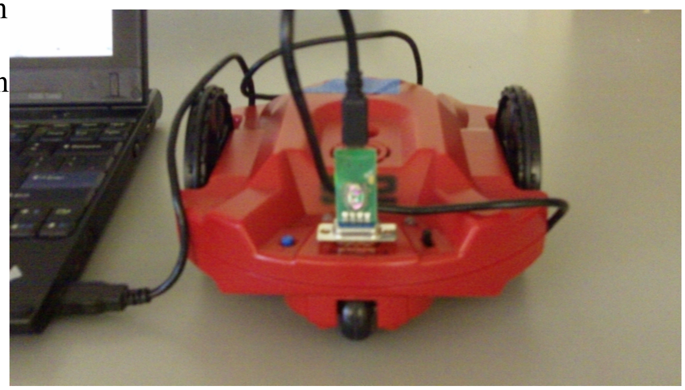

Illustration 1: A USB-serial adapter and USB cable are used to connect the robot to the computer.

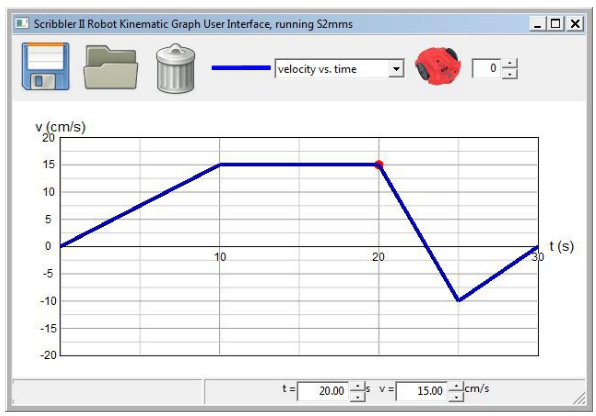

Illustration 2: After drawing a kinematic graph, the student clicks on the red robot icon to send the program to the robot. The red dot highlights the currently selected point, which can be edited by dragging it or by entering values in the text box in the bottom status bar.

Technical Details

An expert can interpret messy data by using their mental models to help sort signal from noise, but novices have to focus on building the model and thus require a clear signal if they are to succeed at constructing their own understanding without having to rely on an authority telling them the desired result. To make an apparatus precise and reliable enough for students to independently test their understanding, I sought an educational robot that could achieve my design goal of 1mm/s and 1mm/s^2 accuracy in velocity and acceleration. I finally settled on the Scribbler II because of the submillimeter resolution of its wheel encoders, and powerful propeller processor, but I still had to reprogram its motor driver in a combination of assembly language and its native spin language to move with precise constant velocity and acceleration.[16] Measurements with a motion detector confirmed that it fully met the design specifications.

The next step in the project was to create the graphical user interface through which students would interact with the robot. I used theVpython[17] and wxPython modules of the python programming language to create an interface that runs on current windows computers, and downloads both data and all necessary programs to the propeller processor on the robot.[18] The entire project took several months of full time work, plus further part time work during two consecutive school years. I have also developed a working mac version, but at the current stage it is not professionally packaged in an installer and requires some programming expertise for the user to install.

Lesson Plans

I have used the robots for two years as the fundamental kinematics apparatus in my physics classes. About two dozen teachers have also purchased robots and software and used this approach. In particular, in the summer of 2014, twelve teachers attended a four-day workshop at The Science House at NC State University, and gave the curriculum materials a complete review and thorough overhaul. The overall curriculum sequence and every activity were revised according to the input from this group of experienced educators.[19] Their anecdotal observations confirm my own, that their students enjoy the exercises and become absorbed in the task because they want the test to work precisely. Some students voluntarily stay after class and keep working to avoid being left with the uncomfortable sense of incompleteness created when the test does not work.

In practice, students work on the robot labs in groups of three or four (I purchased enough for two robots per group). Each group has a computer available to program the robots. To introduce constant velocity motion, students take measurements of a robot I program to move with a single constant velocity, and then write their first program by drawing a position vs. time graph to make their second robot match. Students develop other aspects of position vs. time graphs by solving exercises that I give them. When asked to make two robots travel for the same time with different velocities but end at the same place, students must distinguish distance and position and figure out how initial position shows up on the graph. When asked to match a robot that I program to go forwards and backwards, students have to figure out that a negative slope will reverse direction. Asking students to program one robot to move with several constant velocity segments and the second to have the same average velocity helps create a strong foundation for the study of accelerated motion. This last type of exercise, in particular, is not easily producible with any other apparatus.

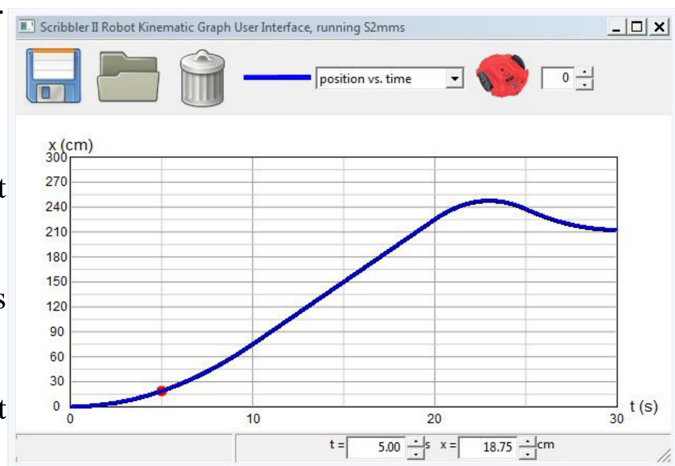

Illustration 3: A position vs. time graph that matches the velocity vs. time graph in illustration 2. When started simultaneously, robots programmed with the two graphs run side-by-side to within millimeters. The red dot highlights the midpoint of the first segment, which can be dragged (or set by entering values) to curve the segment. A parabola is drawn between the two endpoints and the midpoint.

With little need for an introduction to velocity vs. time graphs, students are asked to program both robots themselves, one with a position vs. time graph and the second with a velocity vs. time graph to match it. Their first lesson involves discovering that a velocity vs. time graph represents the motion differently from a position vs. time graph. After matching a simple one-segment position graph, students are encouraged to take full control of the inquiry process by gradually or rapidly increasing the complexity of the problems they pose themselves until they master graph matching involving up to four segments and both directions of motion. In one memorable occasion, the two robots went in opposite directions in the middle of a complex motion. "Why did that go wrong?" and "We have to fix this!" and "I think I have an idea." were the immediate reactions. Then the students went back to work without giving me time to get a word in edgewise. The constant velocity unit ends with a lab practicum in which students have to rescue a captive Einstein bobble-head while avoiding robot sentries pacing back and forth in front of their path. Students were excited and engaged when it came time to test their solution.

To introduce accelerated motion, students are asked to program a robot (starting from rest) with a sloped line on their velocity vs. time graph and predict the distance traveled. Over half the groups simply multiply the final velocity by the time and experience some suprise when their robot only goes half the predicted distance. Racing this accelerating robot side-by-side against two constant velocity robots - the second programmed with the average velocity, and the third with the final velocity – helps students develop their own explanation for why the factor of one-half is necessary, and also emphasizes the concept of area under the curve and its relation to average velocity. As they explore motions with non-zero initial velocities that involve slowing down as well as speeding up, the students continue to compare the accelerating robots to constant velocity robots with the same average, initial or final velocity, thus reinforcing the relationships among the velocity graph, the mathematical operations of area and slope, and direct observation of motion.

I use the robots to turn many classic physics problems into lab practicums, for example the accelerating patrolman pursuing the constant velocity speeder, a subway accelerating, traveling with constant velocity, and decelerating between stations, or two cars braking to avoid a head-on collision. With the velocity graph as the primary problem-solving tool, some students take a graphical approach, while others rely primarily on equations derived from the slope or area of the graph. Testing with the robots provides a vivid illustration when the mathematical solution is no where close (due to algebra errors), when the graphical solutions is (almost always) in the ballpark, and when a fully correct mathematical solution is very precise, emphasizing for all the value of both the graphical estimate and the mathematical solution.

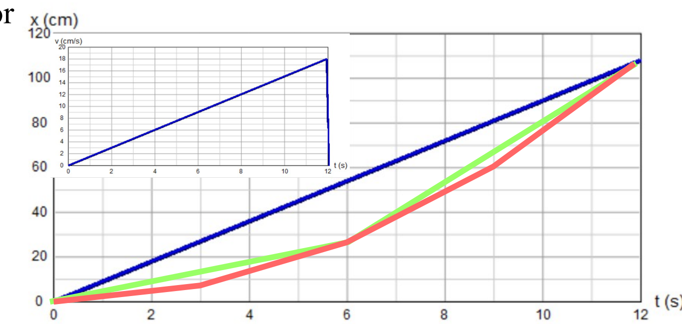

Illustration 4: Successive approximations to an accelerated motion (velocity graph inset) are programmed using a position vs. time graph with one (blue), two (green), and four (red), constant velocity segments, and tested by racing them against the accelerating robot. By six segments (not shown), the motions are barely distinguishable and students can envision that the limiting sequence will end with a smooth curve.

After studying velocity vs. time graphs and deploying them as a problem-solving tool, students develop an understanding of position vs. time graphs for accelerated motion by directly observing several steps in a limiting process that ends with a curved graph (illustration 4). They use a velocity graph to program a robot to start from rest and accelerate, then race it against a series of robots programmed with constant velocity segments on a position graph. The simplest approximation is a single constant velocity segment – i.e. the average velocity, but this matches the accelerating robot only at the initial and final points. Students then program the second robot with two, three, four, and six constant velocity segments, each with the same change in position for its respective time interval as the accelerating velocity vs. time robot. At each step of the limiting process, they see the motion of the two robots match more and more precisely, as the discrete segments on the position vs. time graph approach a curve. This global approach to the limit gives students a better tool to understand the whole graph shape, which seems to escape far too many even after grasping the idea of the slope of the tangent line through a limiting process applied locally at a point on the graph. The idea of a limiting process composed of constant velocity segments then becomes a tool to understand more complicated motions involving slowing down, traveling in the negative direction and changing directions.[20]

Throughout the kinematics curriculum, the robots tie the graphs and math directly to observations of real motions. From the simplest to the most complex multi-segment motions, there was not a single problem that could not quickly and easily be demonstrated with a real moving object.

TUG-K Results

Over a period of two years, I used this approach with 99 students in six sections of non-honors physics at my private, independent high school. All students in the school are required to take physics in their junior or senior year, so the students in my sections of physics included the students with the weaker mathematical backgrounds. They improved from a pre-test average of 29.3% on the TUG-K to a post test average of 73.9%, outperforming the post instruction average of 40% from a study of over 500 college and high school students conducted by Beichner, et. al.[2]

Conclusion

The curriculum I described makes use of the robots from beginning to end of the kinematics sequence, but useful demonstrations could be performed with even one robot. For quizzes and in-class polls, I would demonstrate a robot I had programmed to the class and they would have to draw or select graphs with the correct shapes. With just two robots, one can generate the conceptual motion comparison exercises featured in McDermott's work.[15,3,4,5] I even made use of robots to teach vector addition and used two robots (one pulling a whiteboard while the other crossed it at right angles) to introduce projectile motion. More detailed descriptions of lessons, student reactions and additional ideas are available in the complete curriculum[19] and on my blog.[18]

Because of the small sample size, it cannot be ruled out that the pre and post test results are due to confounding factors such as characteristics of this particular group of students, other aspects of my own teaching style or the length of time that I spent on kinematics. Nevertheless, the results are strong enough to indicate that kinematic robots give physics teachers another valuable tool for teaching kinematics.

1 A. S. Lillard, *Montessori the Science Behind the Genius* (Oxford University Press, 2007), p. 174-175.

2 R.J. Beichner, "Testing student interpretation of kinematics graphs," Am. J. Phys. 62, 750 (Aug. 1994).

3 D.E. Trowbridge and L.C. McDermott, "Investigation of student understanding of the concept of velocity in one dimension," Am. J. Phys. 48, 1020 (Dec. 1980).

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7 R. Hake, "Interactive engagement vs traditional methods: A six thousand student survey of mechanics test data for introductory physics," American Journal of Physics 66, 64 (1998).

8 M. Wells, D. Hestenes, and G. Swackhamer, "A modeling method for high school physics instruction," American Journal of Physics 63, 606 (1995).

9 M. Rosenquist and L. McDermott, "A conceptual approach to teaching kinematics," American Journal of Physics 55, 407 (1987).

10 R. K. Thornton and D. R. Sokoloff, "Learning motion concepts using realtime microcomputer based laboratory tools," American Journal of Physics 58, 858 (1990).

11 R. J. Beichner, "The impact of video motion analysis on kinematics graph interpretation skills," American Journal of Physics 64, 1272 (1996).

12 For example,The Ultimate Graphing Challenge by http://www.theuniverseandmore.com/, the Phet Moving Man simulation http://phet.colorado.edu/en/simulation/moving-man, and the Graphs and Tracks Model by Wolfgang Christian and Mario Belloni http://www.compadre.org/osp/items/detail.cfm?ID=12023 .

13 J. Laverty and G. Kortemeyer, "Function plot response: A scalable system for teaching kinematics graphs," American Journal of Physics 80, 724 (2012).

14 R. Mitnik, M. Recabarren , M. Nussbaum, and A. Soto, "Collaborative robotic instruction : A graph teaching experience," Computers & Education 53 330–342 (2009).

15 Currently available for $129.99 from Parallax, Inc. http://www.parallax.com/product/28136 .

16 The Scribbler, as most educational robots, comes pre-loaded with software designed to help students learn robotics, develop problem-solving and programming skills, and apply a little physics, by programming the robot to perform autonomous tasks such as follow a maze, avoid obstacles, or trace a geometrical figure. For these purposes, it does not require a mathematically precise motor driver. As long as the robot completes the desired task in a reasonable (or fastest possible) time, it does not matter whether the velocity or acceleration are constant. However, my goal was to use a robot as a physics apparatus, rather than to teach robotics with physics applications. In the development process, I ruled out more than a dozen other possibilities, including building my own robot from parts, because the hardware lacked the desired precision, or the microprocessor and its available programming languages were not up to the task.

17 Vpython version 6 is available from http://www.vpython.org and comes with the wxPython module. These were convenient for creating the graphical user interface because I was already familiar with them from other physics

education applications. c.f. R. Chabay and B. Sherwood, *Matter and Interactions* (Wiley 2010).

18 My blog at http://aphysicsmicrocosm.wordpress.com/ describes the lessons in more detail. A school site license for the software is currently available for $100 by contacting me by e-mail at matt_greenwolfe@caryacademy.org , and will soon be available through an online storefront connected to the blog. It installs all components with a single standard windows installer. You may also contact me for a version that runs on MAC computers, although it is not fully-featured and requires some minimal programming experience to install, as I have not yet packaged it in a professional installer.

19 The curriculum materials are available for download from the American Modeing Teachers Association at http://modelinginstruction.org/teachers/resources/, and for AMTA members is also available in the resource section of the members area at https://www.eweblife.com/prm/AMTA.

20 When they subsequently encounter difficulty, it is usually sufficient to suggest students draw a one-segment approximation to the position vs. time graph (and note whether its slope is positive or negative) followed by a two-segment approximation (and note whether the magnitude of the slope is increasing or decreasing). Since they've already seen a lengthier limiting process, most students are then able to draw or interpret the curved position vs. time graph.

Matt Greenwolfe has earned a bachelors degree in physics from from Washington University in St. Louis and a PhD in physics from The University of Michigan. He is a past president of the American Modeling Teachers Association, http://modelinginstruction.org/. He has been teaching at Cary Academy since 2000, and previously taught at Sayre School in Kentucky and Union College in New York. matt_greenwolfe@caryacademy.org, http://aphysicsmicrocosm.wordpress.com

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