Physics With Robotics
Using LEGO® MINDSTORMS® in High School Education

William Church[1], Tony Ford[2], Natasha Perova[3], Chris Rogers[4]

[1]Littleton High School, Littleton, New Hampshire, [2]Redcliffe State High School, Redcliff, Queensland, Australia, [3]Harvard Graduate School of Education, Cambridge, MA, [4]Tufts University, Medford, MA
Email: wchurch@littletonschools.org; anthonyford23@gmail.com; nperova@gmail.com; crogers@tufts.edu

Abstract

Integrating robotics activities in science curriculum provides rich opportunities to engage students in real world science and help them to develop conceptual understanding of physics principles through the process of investigation, data analysis, engineering design, and construction. In addition, students become more confident learners and develop better problem-solving and teamwork skills. In this paper we describe a successful use of LEGO® MINDSTORMS® in designing robotics-based activities for teaching high school physics classes. Students design and perform novel science investigations with a toolset that helps them achieve a high reproducibility in their experimental designs. Several example projects that utilize LEGO MINDSTORMS are presented.

Physics with Robotics

Based on the authors' experience, students have difficulty learning for learning's sake, especially in physics classrooms. Students thrive, exhibiting a great deal of enthusiasm and ownership, however, when they have an applied, real world challenge such as an engineering problem to solve or a novel science investigation to perform. By allowing them to solve problems where the answer is not already on an answer sheet somewhere, students learn confidence, problem-solving, teamwork and gain a better understanding of the underlying concepts. Engineering problems, based on real-life situations, provide students with meaningful reasons to learn new material and a powerful educational framework that gives them an opportunity to transfer their knowledge to new situations (Rogers, 2009). Use of engineering problems also helps to focus students' attention on the process as well as the final outcome. Novel science investigations provide students with opportunities to create hypotheses, build experiments, generate models to represent findings, draw conclusions, and communicate their results (Charney et al., 2007, Collins et al., 1989). All of these are essential inquiry skills that students should learn and can be as useful to the student as the content itself (American Association for the Advancement of Science, 1989).

Robotics gives students opportunities to represent their ideas in different ways and utilize 3D artifacts (robots) to contextualize their learning and help them communicate their ideas and understandings. As students learn new material, mastery comes when they can represent their ideas in different ways such as writing, math, construction, and verbal debate (Goldin & Shteingold, 2001). Well designed activities using robotics give students rich opportunities to write about their ideas; utilize mathematical tools and represent their findings via mathematical models; construct 3D artifacts that embody their ideas and solutions; and engage in verbal debate as they work through robotics based design problems and science investigations. The utilization of 3D artifacts such as robots allows students to contextualize their knowledge and provides them with communication opportunities involving direct discussion of the artifact as well as gesturing and pointing to the artifact (Roth, 1996).

In his book, Making Learning Whole, David Perkins discusses the importance of introducing students to the "whole game" rather then isolated pieces of a discipline (Perkins, 2008). To account for the subject complexity, the role of the educator is to create entry points for students appropriate to their learning progression. Adding robotics activities to science classes provides students with opportunities to play the "whole game" and engage in real world science through design, construction, and testing of their own experiments. They perform novel science investigations with a toolset that helps them achieve a high level of precision in their measurements and reproducibility in their experimental designs (Church, Ford, & Perova, 2009). There are many such toolsets available, but we will concentrate on the LEGO® MINDSTORMS® kit because it provides students and

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teachers with a high number of project possibilities without significant equipment constraints. Additionally, many students are familiar with LEGO, their modular design allows for multiple solutions to a given assignment, and the sensors and motors that are compatible with LEGO MINDSTORMS allows high school physics students to engage in a very diverse set of engineering and science activities. For example, students can explore the limits of a sound sensor when designing better ear protection, investigate the phenomena of reflection and light intensity with light sensors, experiment with magnetic field forces to create a navigation system, and engineer gear ratios when designing a drag car. What is fundamental to these robotics based activities and what makes them rich learning experiences is the synthesis between science investigation and engineering design, a synthesis that closes the gap between "the concepts and skills of physics and the practical use of those skills [helping] students take what the learn in the classroom and use it in the rest of their lives" (Church, Ford, & Perova, 2009, p. 9).

Example Activities

What follows are example projects that utilize LEGO MINDSTORMS in high school curricula. For each example, we will present a project overview and learning objectives. At least two of these projects will be available for evaluation at the conference. More examples are provided in our book, Physics With Robotics – An NXT and RCX Activity Guide for Secondary and College Physics (Church, Ford, & Perova, 2009).

Testing Speed vs. Acceleration of Drag Cars. Students work in a team to figure out which is more important in a drag race – Speed or Acceleration. After a design/build iteration, students use a rotation sensor to measure distance, speed, and acceleration of their car. They upload, view, and analyze motion graphs via the data logging function of a LabVIEW™ program. The learning objectives for this project are:

- Describe motion in terms of speed and acceleration.
- Compare various factors that may affect speed and acceleration of an object including power, time of travel, gear ratio and wheel size.
- Utilize a scientific experiment to inform the engineering design process with the goal of maximizing acceleration and speed.

Simple Harmonic Motion. In this experiment, students use a LEGO microcontroller and an ultrasonic sensor to investigate the change in vertical motion of an oscillating spring. Calculations of the amplitude and period can be made using the data from the resulting graph. The learning objective for this project is:

- Study periodic motion and the characteristics of a displacement graph that represents simple harmonic motion.

Ten Second Timer. In this project, students will use their understanding of simple harmonic motion to engineer a mechanical 10-second timer that utilizes an external pendulum based clock. Students work in teams to design a pendulum and sensor package to count swings. Their system is successful if it marks 10 seconds with an audio and/or visual display (Figure 1). The learning objectives for this project are:

- Use an idealized system (simple pendulum) to make predictions about the period of a physical pendulum.
- Apply predicted performance of a physical pendulum in the engineering design process of a mechanical timer.
- Use MINDSTORMS sensors to measure the performance of the system and compare with a calibrated timer such as a watch.

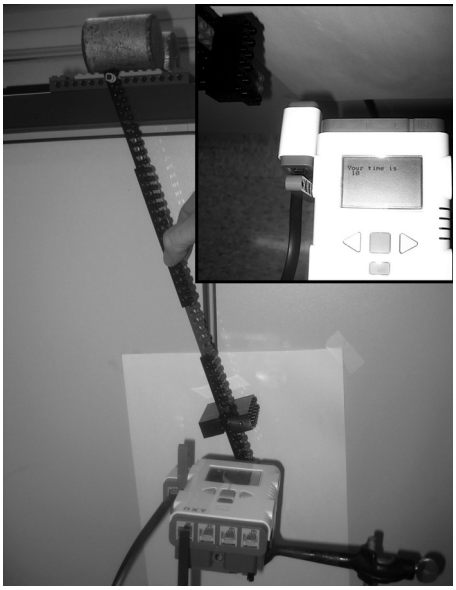

Figure 1. Student built "Ten Second Timer" based on a LEGO beam based physical pendulum. In this design, the students' timer counts swings with a light sensor and indicates when 10 seconds has elapsed via a visual display on the screen and an audible tone.

Microphone Sound Reduction. In this activity, students explore sound waves. Specifically, they use a LEGO sound sensor to explore a sound wave's intensity by designing experiments to investigate the variables that affect the measurement of a sound wave's loudness. For example, students explore variables such as the distance between sound source and microphone, sound wave direction and shape (approximated by a cone or sphere), the frequency response of the MINDSTORMS microphone, and the conductivity of sound through different media. Finally, they design better "ear" protection for the sound sensor by taking what they have learned through the science investigation and applying it to an engineering design problem. The learning objectives for this project are:

- Describe sound waves in terms of a transfer of energy

- Measure the loudness of a sound wave and relate this measurement to a wave's amplitude, energy, power, and intensity.
- Create an experiment that investigates which variables affect the measured loudness of a sound wave.
- Engineer ear protection that reduces the sound levels measured by the microphone.

Discussion

When we developed the activities outlined in this paper, we based their design on own classroom observations, shared observations with other instructors, and relevant literature. Claims related to student learning through our activities are based on observations of hundreds of students in our respective institutions that span secondary and post secondary levels in United States and Australia. Example observations are outlined below.

When compared with other velocity vs. acceleration activities we have conducted, we observe more students engaged in our drag car activity that exhibit a high level of ownership and investment in their work. With this ownership and investment, and scaffolds built into our activity, students work through their confusion regarding the concepts of velocity and acceleration via design iterations, artifact mediated conversations with teammates and teacher, feedback from real-time motion graphs, and performance feedback. This last point – performance feedback -- makes a big difference in the classroom. Students want to achieve the goals of the assignment. In this assignment, they want their LEGO cars to have a high velocity or have a high acceleration. Toward achieving this goal, they invest a great deal of energy in problem solving. When demonstrating and explaining their drag car creations, they confidently showcase their improved understanding of velocity and acceleration.

This exploration and refinement is also encouraged in the ten-second timer and sound reduction activities. As with many secondary level physics activities, complex mathematical relationships are involved. By using the hands-on robots and the data coming in from sensors to test and check the results of their design ideas, a greater diversity (compared with our past observations from teaching the same content via different teaching strategies) of students move past their confusion with the complex mathematical relationships to confidently create solutions to design challenges. We observe them using correct physics reasoning to explain the performance of their designs.

We recognize that our evidence is anecdotal and that more formal studies are needed.

Conclusion

Using LEGO MINDSTORMS robotics activities to teach physics concepts creates an effective learning environment for conceptual knowledge development through the process of design, construction and experimental testing. In this paper, we described several classroom-tested activities that target the topics of speed, acceleration, simple harmonic motion, and sound waves. We found that these experiments provide a powerful educational framework by combining science investigations and engineering design, where students not only learn the concepts and the skills of physics but the practical application of their knowledge as well. Students have opportunities to develop their teamwork and communication skills and become more independent and confident learners.

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