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Modern Sensing and Computerized Data Acquisition Technology in High School Physics Labs*

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Under a National Science Foundation (NSF) funded GK–12 Fellows project, a solution to invigorate high school students' interest in science, technology, engineering and mathematics (STEM) careers is being examined and implemented. For an overview of our strategy and results from the first year of the project see below.

Keywords: data acquisition; GK–12 Fellow; high school; lab experiment; outreach; physics; sensor; STEM

INTRODUCTION

AFTER WORLD WAR II, a bitter rivalry ensued between the United States (US) and the Soviet Union developing into the Cold War. In this age, scientific and technological superiority was of paramount concern for both countries as they competed to attain military dominance. The balance of power shifted to the Soviet Union in October 1957 with successful launches of Sputniks I and II [1–3]. The American response to these events came with the creation of the Apollo programme in 1961 by President Kennedy, who challenged the USA to put a man on the moon before the turn of the decade. The resulting decade-long race to the moon led to a surge of student enrolments in STEM programmes in the American universities [1, 4] and energized the American research enterprise [5–9].

After the end of the Cold War in the late 1980s America faced different challenges. First, after a series of strikes on American interests abroad in the 1990s, on 11 September 2001, terrorists attacked New York City (NYC) and Washington D.C. In the aftermath of these attacks, a severe clampdown on immigration to the US ensued. Second, since the late 1990s, the service-sector of the American economy began to shift its operations overseas to low-wage countries, following the model of the manufacturing-sector from an earlier era. Thus, increasing import of services and manufactured goods from abroad has recently led to growing trade deficits with countries such as China and Japan. Consequently, in recent years, a chorus of civic- and business-leaders has argued [10–13] the paramount importance of protecting American leadership in scientific discovery and technical innovation, to enable the US to bridge the gap with its trading partners and to respond to the asymmetrical terrorist threats through the development of superior technological solutions. Unfortunately, American leadership in science and technology is threatened by a perennial disinterest in STEM disciplines among college-bound students. Furthermore, the stringent immigration laws enacted in response to the events of 11 September 2001, have significantly reduced the inflow of foreign-born/trained science, maths and engineering students, who have typically supported the research enterprise at the nation's universities.

To sustain the US quest to develop an 'innovation economy', our universities must attract, educate and graduate a large number of qualified scientists and engineers. In responding to this task, the universities face the following challenges:

1) engineering is held in less esteem than other professions;
2) maths and science are not perceived as cool by high school students;
3) society discourages female high school students from becoming engineers;
4) the typical engineering curriculum is more rigorous than other majors, causing high school graduates to shy away from the engineering discipline.

The problem is further exacerbated by negative stereotypes of scientists and engineers held by teenagers.

To develop a creative solution to the problem of attracting more students to STEM disciplines, as engineers, we must begin by analysing various characteristics of this problem. Thus, we begin by scrutinizing the American K–12 educational environment and discover that the problem is not amenable to any single solution since it spans the

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entire educational experience of K–12 students. For example, in the elementary grades a major preoccupation is literacy (i.e. reading and writing). Unfortunately, this often means that maths and science are accorded a lower priority, or even are shunned. While in middle school, students are required to take earth and biological sciences, in high school, these science courses are repeated as requirements but physics is left as an elective. Without a rigorous education in maths, which forms the foundation of analytical sciences [14], when the relatively few high school students encounter a physics course, their educational understanding and achievement are hampered since abstract concepts and equations lack appeal due to their rigour.

Today's students live in and benefit from a highly technological world, one which includes PlayStation Portable that can play video games and movies, cell phones with video and MP3 capabilities, and personal digital assistants that are as powerful as laptops. Having experienced these technological gadgets, when students enter a lab setting they encounter primitive equipment. Not surprisingly, lack of a modern and challenging lab environment further drives these students away from STEM disciplines.

As one remedy to the malaise afflicting the American pre-college educational system, under an NSF GK–12 Fellows Grant, we have formulated and implemented a solution, which is the subject of this paper. Specifically, over a dozen undergraduate and graduate engineering students have partnered with teachers at four NYC public high schools to integrate modern sensing and data collection technologies into the lab sections of physics and living environment courses. This paper focuses on project activities related to the physics course [15]. Our approach addresses the following key issues:

- The lab is in keeping with the times, that is, students use state-of-the-art equipment in comparison to the equipment used in traditional science labs.
- Sensors and data acquisition tools along with a suitable graphical user interface can provide students with intuitive insights.
- Since manual collection and recording of data is not the principal focus of the lab, students can focus on learning the underlying concepts of the lab and formulating and testing new hypotheses.

Several recent papers [16–18] have reported successful use of robotics technology to attract pre-college students to STEM disciplines. Moreover, [19] suggests using gaming technology to enable engineering education to connect better with today's computer savvy students. In a similar vein, we expect that the modernized physics labs offering interesting exercises will inspire students to learn the fundamental principles of science rather than studying simply to pass a test. We further anticipate that integration of real-world engineering examples as applications of scientific principles and exposure to undergraduate and graduate engineering students will encourage the high school students to consider higher education and professional careers in STEM disciplines.

Overview

The Revitalizing Achievement by using Instrumentation in Science Education (RAISE), project is being implemented under an NSF GK–12 Fellows Grant [20]. The project is led by two engineering and a humanities faculty. The project's partner high schools are: George Westinghouse, Marta Valle, Paul Robeson and Telecommunication Arts and Technology HS. The average SAT score of students from the partner schools is below 850 and fewer than 10 per cent of the students score above 1100, the cut-off for admission to the undergraduate science and engineering programmes in most universities. Moreover, their passing rates on the required standardized science and math exams and graduation rates are alarmingly low (below 50 per cent).

The goals of the project include:

1) enhancing student achievement in standardized exams;
2) inspiring inner-city students to reach high academic standards while acquiring passion for STEM disciplines and careers;
3) providing teachers with technology proficiency;
4) enabling GK–12 Fellows (RAISE Fellows) to hone their communication and leadership skills and develop a deeper appreciation of STEM disciplines.

The RAISE Fellows develop creative and engaging experiments for physics labs by using modern sensing, instrumentation and data acquisition tools along with a user-friendly graphical user interface (GUI) for data analysis and plotting. Use of modern data acquisition tools allows high school students to optimize their time in the lab. Furthermore, in collaboration with teachers, RAISE Fellows make presentations and conduct demonstrations to introduce appreciation of physics topics from an engineering viewpoint to enhance the educational experience of high school students.

TRAINING OF FELLOWS AND TEACHERS

Before being deployed in the four schools, RAISE Fellows receive intensive training during the summer months before the start of the school year [21, 22]. Fellows are first introduced to modern sensing technology and mechatronics. Topics covered include sensors and signal conditioning, actuators and power electronics, hardware interfacing, and embedded computing. In addition, Fellows attend a weeklong teaching workshop to develop their pedagogical skills such as lesson planning and effective questioning techniques,

Table 1. Sensor-based physics activities developed under the RAISE project

Experiment	Description
Air Resistance	An ultrasonic sensor is used to measure the velocity of one or more free falling coffee filter(s) and to show that the filter reaches a terminal velocity due to air resistance.
Buoyancy	A force sensor is used to measure the buoyant force of an object immersed in liquid. Knowing the submerged volume of the object the density of the liquid is obtained.
Conservation of Mechanical Energy	An ultrasonic sensor is used to determine the position and velocity of a tossed ball. Using the position and velocity at various locations, principle of conservation of total energy is verified.
Damped Vibration	An accelerometer is used to find the response of an oscillating mass-spring system from which the damping coefficient and natural frequency are determined. The spring constant is also approximated.
Electromagnetism	A magnetic field sensor is used to verify properties of a solenoid such as uniform field strength within the core, negligible field outside the core, direction of poles formed due to current direction, and attenuation of field as measured axially.
Freefall Acceleration	Using a photogate, the acceleration due to gravity of a free falling object is measured.
Heat Transfer	Using a temperature probe, the rate of cooling and heating of water is measured. Insulating properties of different materials are also investigated.
Magnetism	A magnetic field sensor is used to quantify the magnetic properties of different materials as well as to classify the materials as diamagnetic, paramagnetic, or ferromagnetic.
Projectile Motion	Two photogates are used to measure the horizontal component of the initial velocity of a ball being rolled off a table. Using this value, the range of the horizontal landing is calculated.
Simple Harmonic Motion	An ultrasonic sensor is used to measure the amplitude and frequency of a mass-spring oscillator. From this, maximum velocity and acceleration are calculated and the mathematical model of harmonic motion is verified.
Stability	A force sensor is used to pull a block until the block tips or slides. The critical forces are then computed theoretically and compared with the sensor measurements.
Static and Kinetic Friction	A force sensor is used to pull on a wooden block, sliding over a frictional surface, to determine the coefficient of static friction. Kinetic friction is determined using an ultrasonic sensor that measures the deceleration of a sliding block coming to rest.
Vector Addition	Force sensors are used to find the tension in two strings attached to a mass. The resultant force is then computed.

student behaviour and cognition, learning theory and styles, classroom/group management skills, effective communication and presentation skills, active learning techniques, project-based learning and evaluation methods.

Teachers from the RAISE-supported schools also attend a weeklong technical workshop focused on modern sensing technologies. The workshop is conducted by the engineering faculty and the RAISE Fellows and it provides the teachers with insight for class activities and prepares them to become technology resources in their schools. A byproduct of this training is that teachers and Fellows have the opportunity to become acquainted with and bond with one another as they begin planning for the upcoming year.

Sensor-based physics experiments

Thirteen sensor-based physics experiments have been developed (Table 1). These experiments are intended to support the Regents Physics Lab. In New York State students must pass three science Regents exams with a score of 60% or better to graduate from high school with Regents diploma. Regents Physics is an elective taken by fewer than 10 per cent of students in the partner schools. Students have strong intuitive skills and poor analytical skills. Thus, it is the purpose of these labs to enhance their intuitive skills and build their analytical and maths skills. Two sample example labs are described below.

Experiment on buoyancy and fluid density is designed to verify the density of a fluid while illustrating Archimedes's principle of buoyancy. Students are first presented with buoyancy effects in design of barges, ships and submarines. Having seen the applications of this concept, students become motivated for further learning and exploration because they realize the legitimacy of the topic. A conventional way of measuring the density of a fluid involves finding the mass of a container, then filling it with the test fluid and finding its mass again to determine the mass of the fluid from difference between the two mass measurements. Knowing the volume of the container, the density of the fluid is computed using the mass to volume ratio. Next, Archimedes' principle states the following: 'An immersed body is buoyed up by a force equal to the weight of the fluid it displaces', that is

$$F_b = \rho_f V_d g$$

where F_b is the buoyant force, ρ_f is the density of the fluid, V_d is the displaced volume and g is the freefall acceleration. The buoyant force is countered by the weight of the body mg. The difference between the two produces a net force of

$$F_{net} = mg - \rho_f V_d g$$

For an immersed body, using a force sensor, one can measure the net force at different levels of fluid

Fig. 1. Buoyancy experiment: a mass, suspended on a force sensor, is placed in a liquid to examine Archimedes Principle

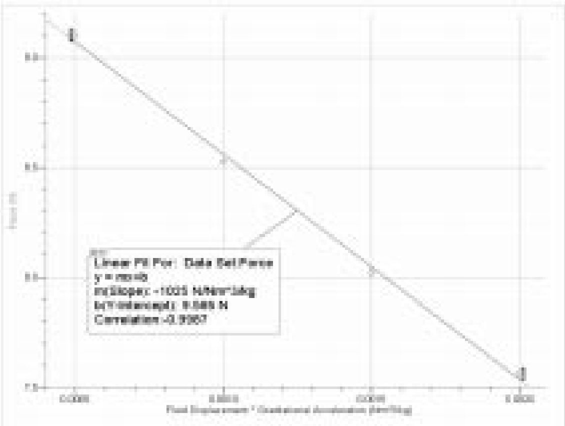

Fig. 2. Sample result of buoyancy experiment

displacement (Fig. 1). The plot between the net force (i.e., F_{net} and the product of volume displacement and gravitational acceleration (i.e. $V_f g$), should yield a straight line with the slope of the line representing the density of the fluid (Fig. 2). This density is then compared to that obtained using the conventional method. By doing this experiment students are presented with an alternative way of measuring fluid density while being familiarized with the concept of buoyancy.

Experiment on damped vibrations. The phenomenon of vibrations is ubiquitous. Periodic phenomena occur throughout nature. This is evident on a microscopic scale as electrons orbit the nucleus as well as on a colossal scale as the earth revolves around the sun. Without the vibration of electromagnetic fields, the world would be dark and cold. With just a few examples, it is apparent that students should be familiar with vibrations and their characteristics. In the examples cited above, as well as many other periodic phenomena, the underlying vibratory systems experience minimal energy loss and thus exhibit properties of simple harmonic motion. When energy loss is significant, the oscillation is no longer simple, but damped in which case the displacement, velocity and acceleration of an oscillating body will resemble an exponentially decaying sinusoid. Although damping is not part of the traditional high school physics curriculum, in the spirit of presenting real-world applications of physics, a lab on damping effects is introduced.

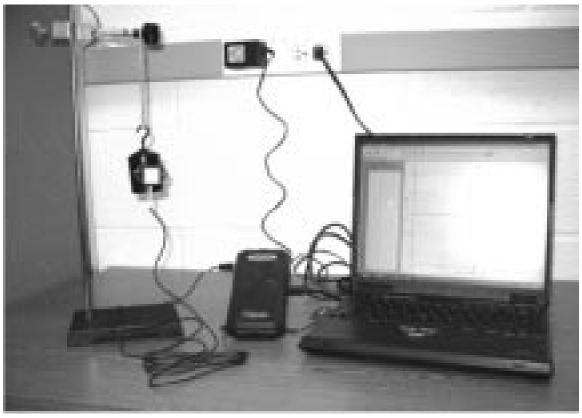

Fig. 3. Damped vibrations experiment: Mass-spring (rubber band) system with accelerometer

We begin our investigation of damping with a premise in the form of the following question: 'why does a child swinging on a playground swing eventually come to rest?' Equivalence between a pendulum (child on a swing) and a mass-spring system is first described. Students then examine the above question by attaching an accelerometer sensor to the mass of a mass-spring system (Fig. 3). The sensor records the acceleration of the mass—a smooth decaying sinusoidal waveform (Fig. 4). From this curve, the amount of damping present in the system, the period of vibration, the natural frequency of the system, and the equivalent spring constant can be determined. All of the measured quantities are then reflected back to the playground swing question and conclusions are drawn regarding factors that affect the motion of the body.

Classroom implementation

It is commonly held that high school students who excel in maths and science courses succeed in high school and continue their education in college. The difficulty involved in mastering these subjects presents great challenges for students and for the educational system. Moreover, a lack of fully prepared and effective teachers is further limiting the achievement of students in STEM disciplines in US K–12 schools. Teachers lack adequate professional preparation, budgets are limited, science and maths areas suffer from acute teacher shortages. In fact, the sheer shortage of teachers [23] has led to overcrowded classrooms, further hindering the student achievement in these disciplines.

Motivated by the recognition of these needs, RAISE Fellows have been mobilized to:

1. introduce technology to in-service teachers to enhance their technical proficiency;

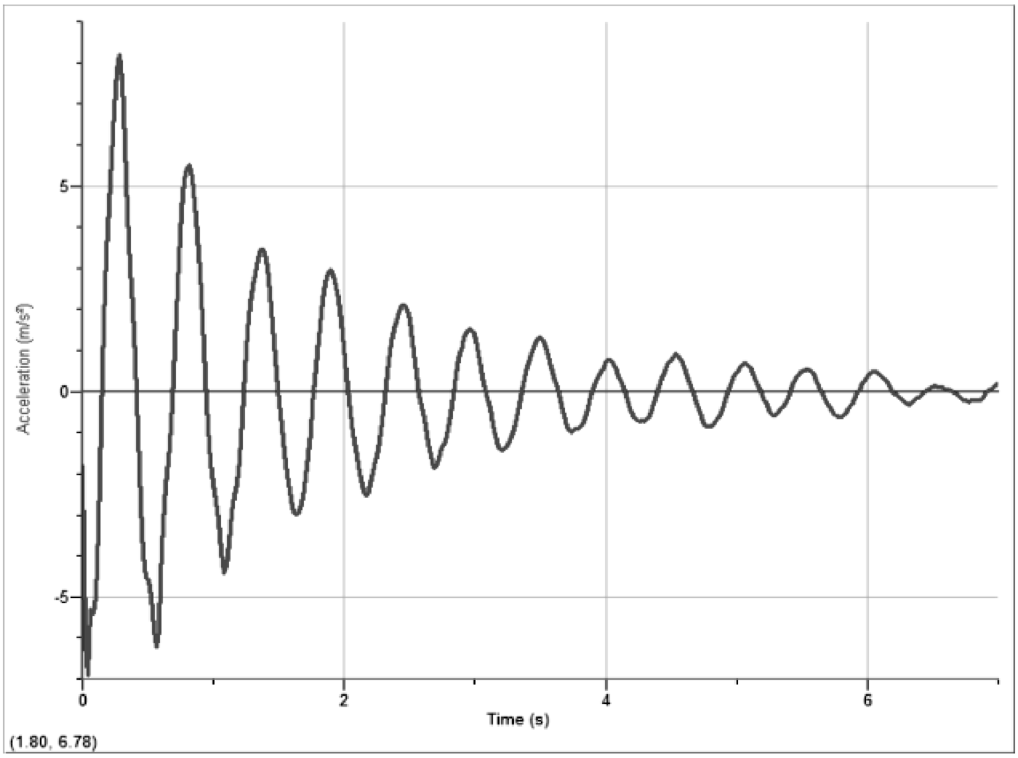

Fig. 4. Sample result of damped vibrations experiment

2. serve as an additional resource in the classrooms and labs to provide individual attention to students;
3. interact with students as their mentors and coaches to stimulate their interest in math and science;
4. serve as role models to motivate students to pursue careers in STEM disciplines.

Each of our partner schools has been equipped with four computerized lab setups which allow for groups of four to five students per setup. The experimental modules are designed in a way that every member of the group has an active role in the experiment. Furthermore, team members must have constant interaction among each other to complete the lab assignment properly. For example, one student holds the sensor, another operates the computer, the third works with the equipment and the fourth acts as a manager and monitors that everyone is synchronized. The students have the opportunity to switch roles as most modules have multiple trials. This method of assigning differentiated tasks keeps students engaged and prevents negative behaviour before it starts.

Incorporating the Logger Pro Software [24] allows the instructor to convey the material through a wide range of learning styles:

1. the graphical user interface displays sensor measurements through which visual learners easily pick up the concept;
2. the team-based tasks require group effort which benefits auditory/verbal learners;
3. the hands-on lab activities aid the tactile/kinesthetic learners, who grasp the concept by doing the experiment.

OUTREACH EVENTS

Several outreach events, planned and conducted by the RAISE project team are described below.

- On 2 November 2004, RAISE Fellows conducted a workshop on modern sensing and data acquisition technology and they introduced Vernier sensors to 20 teachers of science and maths at George Westinghouse HS.
- On 22 January 2005, RAISE Fellows conducted a professional development day for 19 NYC STEM teachers from non-RAISE supported schools. The participating teachers ranged from elementary to high school levels.
- On 20 April 2005, a career day programme was held for students from high schools participating in the RAISE project. The event was attended by over 100 students and teachers. The climax of the event was the showcase of mechatronics-enabled projects, some of which were developed by the RAISE Fellows.
- On 20 May 2005, a regional GK–12 grant holder's conference was held at Polytechnic University. At this conference four GK–12 projects at three NYC universities showcased their efforts. This event allowed Fellows, teachers and the project leaders from the four GK–12 projects to exchange ideas. Many GK–12 Fellows made

presentations to disseminate the results of their efforts. The event was attended by NSF's GK–12 programme team and also by personnel from the NYC Department of Education.

Preliminary impact

Impact on RAISE Fellows

Having seen the value of the programme during the first year, more than half of the RAISE Fellows (seven out of twelve) applied to continue with the programme for the second year. In fact, five undergraduate Fellows from the first year of the programme are now pursuing graduate education and are serving as graduate Fellows. The Fellows are receiving ample opportunities to convey technical concepts in an effective manner to a non-technical audience which is sharpening their communication and presentation skills. The improved communications skills are not only enriching Fellows' academic careers now, but will also serve them in their future academic and professional endeavours. Many Fellows report that they are able to convey to the students the relevance of science taught in high school to real-world problems. In addition, Fellows overwhelmingly feel that their experience with the project is helping them to enhance their own understanding of science. Finally, by serving as role models to youngsters, the Fellows are developing skills that will aid them to become leaders in their respective fields and better informed citizens in the future.

Impact on students

This project aims to provide opportunities to high school students to develop, apply and enhance their STEM related skills. Although it is early to assess the impact of the programme on student achievement, the following observations are noteworthy. A majority of the students see two components of the GK–12 Fellows project *viz.*, the sensor-based labs and the presence of Fellows as the areas expected to yield the greatest educational value *vis-à-vis* other aspects of the courses (e.g. readings, lectures, discussions, group work, etc.). The high school students are receptive and appreciative of the new sensor-based activities in their classrooms and have reported that the lab component is their favorite aspect of the science course. Many students report that the sensor-based labs are more helpful in understanding science concepts than the traditional labs. Finally, many students have expressed interest in continuing their education at the college level in STEM disciplines.

Impact on High School teachers

This project provides opportunities for professional development of teachers and the expansion of their technological literacy. In addition, RAISE Fellows team with the teachers to serve as science resources in the teachers' classrooms and labs. The project has allowed all teacher participants to integrate sensor-based demonstrations in their classroom lessons and modernize the hands-on lab experiments. Many teachers have rated the programme highly for: helping to explain science concepts to students; providing useful lab exercises; presenting positive role models for their students; helping to improve lab attendance; engaging students' attention; providing information on what is involved in working in science/engineering professions. They treat the Fellows as equals, as visiting engineering professionals and as collaborators in finding ways to improve student learning

CONCLUSION

As the programme enters its second year, so does our ambitious agenda. Through the use of modern sensing tools in high school physics classrooms, the RAISE programme is undertaking to revitalize science education. The RAISE Fellows have designed sensor-based labs that convey physics concepts through the use of modern data acquisition tools. Integrating modern technology into the classroom curriculum will equip students with tools that will benefit them in an increasingly technological society. In addition to student improvement, the Fellows develop their leadership and communication skills which are essential for their engineering careers.

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