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

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***Abstract*—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. This paper provides an overview of our strategy and results from the first year of the project.**

I. INTRODUCTION

After World War II, a bitter rivalry ensued between the United States (U.S.) 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 on October 4, 1957 with the successful launch of the Sputnik I. The Soviets continued to flaunt their power with the launch of the Sputnik II on November 3, 1957 [1—3]. The American response to these events came with the creation of the Apollo program in 1961 by President Kennedy, who challenged the U.S.A. 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 enrollments in STEM programs in American universities [1, 4]. Furthermore, a wide array of theoretical and experimental research conducted in support of the space program benefited the society by leading to the creation of numerous products and processes (e.g., microcomputer, inertial guidance system, etc.). The success of the Apollo program is well documented in scientific publications and mass media [5—9].

The Cold War ended in the late 1980s with the demise of communism in countries that comprised the former Soviet Union. Shortly thereafter, however, new challenges to American leadership of the free world began to arise. First, after a series of strikes on American interests abroad in 1990s, on September 11, 2001, terrorists used passenger airplanes to attack New York City (NYC) and Washington D.C. In the aftermath of the September 11, 2001 attacks, a severe clampdown on immigration to the U.S. 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 a growing trade deficits vis-à-vis countries such as China and Japan. Third, in recent years, a growing 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 U.S. 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, secondary school students. Furthermore, the stringent immigration laws enacted in response to the events of September 11, 2001, have significantly reduced the inflow of foreign-born/trained science, math, and engineering students, who have typically supported the research enterprise at nation's universities.

To sustain the U.S. 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: *i)* engineering is held in less esteem than other professions, *ii)* math and science are not perceived as cool by high school students, *iii)* society discourages female high school students from becoming engineers, and *iv)* 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 analyzing 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 entire educational experience of K—12 students. For example, starting with the elementary grades a major preoccupation of the K—12 educational system is literacy (i.e., reading and writing). Unfortunately, this often means math 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.

Moreover, courses such as marine biology are offered, thus enabling many students to avoid taking physics altogether! Without a rigorous education in math, 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 rigor. To further exacerbate the situation, high schools continue to use lab experiments, which were written decades ago and are accompanied by outdated, turn-of-20th-century equipment. Furthermore, these labs fail to inspire students since they do not connect to practical, real-life applications. The result is, of course, high school graduates with poor appreciation and low enthusiasm for STEM education and careers.

Today's students live in and benefit from a highly technological world, one which includes PlayStation Portable that can play video games and movies, cellular phones with video and MP3 capabilities, and personal digital assistants that are as powerful as laptops, all of which have connectivity to the Internet. Having experienced these technological gadgets of our age, when students enter a lab setting they encounter primitive equipment and perform tasks such as, measure the period of an oscillating body using a manual stroboscope. 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 section of physics and living environment courses. This paper focuses on project activities related to the physics course. One premise of our approach is that the introduction of tools and techniques that scientists and engineers use on a daily basis will remove the stigma of science being boring and generate enthusiastic response from students. Our approach addresses the following key issues:

- The lab is 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. For example, if a student tosses a ball, it would be rather difficult to record the ball's instantaneous velocity at any point in time during its flight. However, by using a position detector (e.g., ultrasonic sensor), interfaced to a computer running a graphing program, the ball's trajectory and velocity can be recorded and presented graphically [15], which renders an abstract concept concretely.
- Since manual collection and recording of data is not the principal focus of the lab, the 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.

II. 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. 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 percent of the students score above 1100, the cut-off for admission to the undergraduate science and engineering programs in most universities. Moreover, their passing rates on the required standardized science and math exams and graduation rates are alarmingly low (below 50 percent).

The goals of the project include: *i)* enhance student achievement in standardized exams, *ii)* inspire inner-city students to reach high academic standards while acquiring passion for STEM disciplines and careers, *iii)* provide teachers with technology proficiency, and *iv)* enable GK—12 Fellows (RAISE Fellows) to hone their communication skills, leadership skills, and develop a deeper appreciation for 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.

III. TRAINING OF FELLOWS AND TEACHERS

Before being deployed in the four schools, RAISE Fellows receive intensive training during the summer months prior to 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 week-long teaching workshop to develop their pedagogical skills such as lesson planning and effective questioning techniques, student behavior 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 week-long 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.

IV. REPRESENTATIVE SENSOR-BASED PHYSICS MODULES

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 less than 10 percent 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 math skills. Two sample example labs are described below.

Experiment on Buoyancy and Fluid Density

This experiment 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 in 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,

$$F_{\mathrm{b}} = \rho_{\mathrm{f}} V_{\mathrm{d}} g \,,$$

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

$$F_{\mathrm{net}} = mg - \rho_{\mathrm{f}} V_{\mathrm{d}} g \,.$$

For an immersed body, using a force sensor, one can measure the net force at different levels of fluid displacement (Figure 1). The plot between the net force (i.e., F_{net}) and the product of volume displacement and gravitational acceleration (i.e., $\rho_{\mathrm{f}} g$), should yield a straight line with the slope of the line representing the density of the fluid (Figure 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 phenomena of vibrations are 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 responses 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.

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 (Figure 3). The sensor records the acceleration of the mass—a smooth decaying sinusoidal waveform (Figure 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.

V. CLASSROOM IMPLEMENTATION

It is commonly held that high school students who excel in math 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 U.S. K—12 schools. Teachers lack adequate professional preparation, budgets are limited, and science and math are areas suffering from acute teacher shortages. In addition, the sheer shortage of teachers [23] has led to over-crowded classrooms, further hindering the student achievement in these disciplines.

Motivated by the recognition of these needs, RAISE Fellows have been mobilized to *i)* introduce technology to in-service teachers to enhance their technical proficiency, *ii)* serve as an additional resource in the classrooms and labs to provide individual attention to students, *iii)* interact with students as their mentors and coaches to stimulate their interest in math and science, and *iv)* 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 behavior before it starts.

Incorporating the Logger Pro Software [24] allows the instructor to convey the material through a wide range of learning styles: *i)* the graphical user interface displays sensor measurements through which visual learners easily pick up the concept, *ii)* the team-based tasks require group effort which benefits auditory/verbal learners, and *iii)* the hands-on lab activities aid the tactile/kinesthetic learners, who grasp the concept by doing the experiment.

VI. OUTREACH EVENTS

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

- On Election Day, November 2, 2004, RAISE Fellows conducted a workshop on modern sensing and data acquisition technology and they introduced Vernier sensors to 20 teachers of science and math at George Westinghouse HS.
- On January 22, 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 teachers.
- On April 20, 2005, a career day program 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 May 20, 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 program team and also by personnel from the NYC Department of Education.

VII. EXPECTATIONS AND ASSESSMENT

For high school students, our goal has been to develop and enhance their STEM skills by offering them opportunities to apply STEM knowledge through lab activities. We are also aiming to revitalize student performance on the Regents Exam of Physics [25]. Moreover, we emphasize oral and written communication and opportunities to work in culturally diverse groups. Finally, we aim for students to acquire an appreciation for STEM careers and an opportunity to pursue such a track should they decide to do so.

For the RAISE Fellows, our goal is to sharpen their communication, leadership, and STEM skills through curriculum planning, lab development, and instructional delivery. In addition, we expect the Fellows to learn to communicate complex engineering concepts to a non technical audience, which will be an essential skill in their future careers as science/technology leaders.

For the high school teachers, we expect them to attain adequate technology proficiency and be able to integrate sensor-based demonstrations in their lesson plans and classroom activities. Moreover, we anticipate that they will improve their pedagogical skills through collaboration and exchange of ideas with engineers.

An independent program evaluator has been retained to assess the degree to which the RAISE project is meeting its stated objectives. It is somewhat early to provide a definitive assessment of the project success in meeting its goals. Nevertheless, the following are the evaluator's results for the first year of the program:

- Teachers at the schools, in general, felt that the presence of the RAISE Fellows is helpful in enriching their courses and have rated the program as having a positive effect on their students.
- More students mentioned labs with sensors as compared to labs without sensors as their favorite component of the program.
- Students in most groups generally felt that the RAISE Fellows provided substantial educational value.
- Several RAISE Fellows have shown instructional skills that suggest that they can be successful teachers with similar populations of students, should they choose to do so.

For many RAISE Fellows, teaching science to high school students for the first time was a challenging experience. Dealing with boisterous and sometimes audacious students while teaching science requires a great deal of perseverance and endurance. Nevertheless, the RAISE Fellows quickly adapted to the classroom environment and learned the following lessons from their first year experiences:

- While the RAISE Fellows are inspired by complex science and math concepts, high school students become easily discouraged. Therefore, the first set of developed experiments had to be revised to accommodate student interest level.
- In order to improve achievement on standardized exams, Regents-type questions have been added at the end of each written lab assignment.
- The attention span of an average high school student is short. As a result the RAISE Fellows felt that there was a constant need to inspire their students to do their best.

As William Arthur Ward once said, "When we seek to discover the best in others, we somehow bring out the best in ourselves." This is the kind of outcome we are attempting to achieve for all the participants in the program.

VIII. CONCLUSION

As the program enters its second year, so does our ambitious agenda. Through the use of modern sensing tools in high school Physics classrooms, the RAISE program 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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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 is 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.

Figure 1—Buoyancy Experiment: A mass, suspended on a force sensor, is placed in a liquid to examine Archimedes Principle

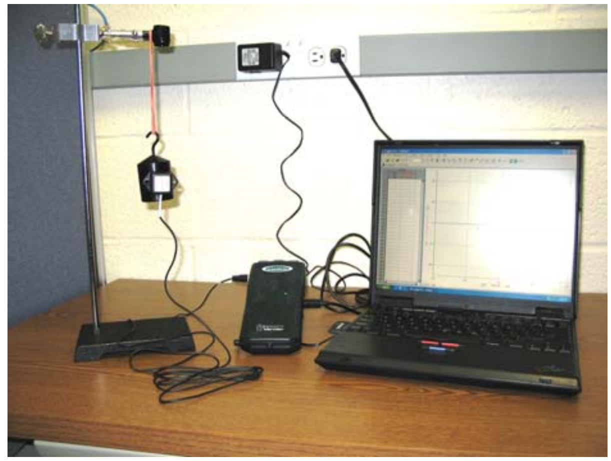

Figure 3—Damped Vibrations Experiment: Mass-spring (rubber band) system with accelerometer

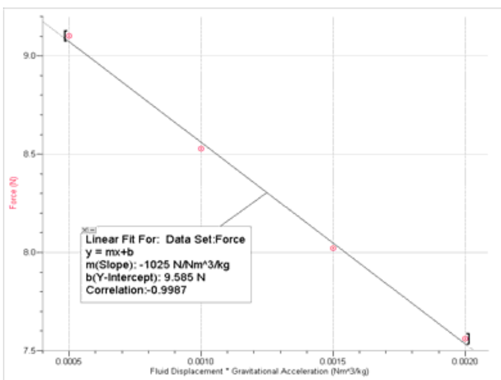

Figure 2—Buoyancy Experiment: Sample result

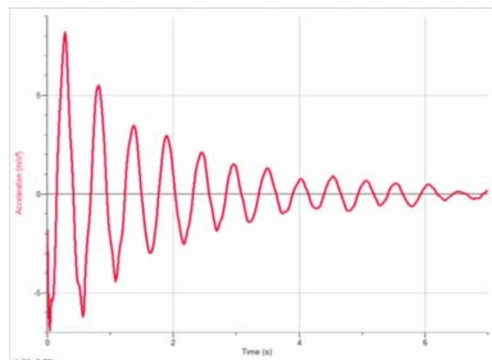

Figure 4—Damped Vibrations Experiment: Sample result