120th ASEE Annual Conference & Exposition
FRANKLY, WE DO GIVE A D*MN
June 23-26, 2013

Paper ID #6412

Integration of Sensors and Low-Cost Microcontrollers into the Undergraduate Mechanical Engineering Design Sequence

Dr. Horacio Vasquez, University of Texas, Pan American

Dr. Horacio Vasquez is an Associate Professor in the Mechanical Engineering Department at the University of Texas-Pan American (UTPA), in Edinburg, Texas. His current research interests are in the areas of control systems, mechatronics, measurements and instrumentation, and engineering education.

Dr. Arturo A Fuentes, University of Texas, Pan American

Integration of Sensors and Low-Cost Microcontrollers into the Undergraduate Mechanical Engineering Design Sequence

Abstract

In most undergraduate engineering degree plans the engineering design curricula include classes such as Introduction to Engineering, Statics, Dynamics, and Mechanics of Solids. They usually do not have laboratory components to help students understand concepts through hands-on experience. This paper presents the development and implementation of an educational low-cost device/tool that can be set up and used by students in and out of their engineering classes to assist their learning. The goal of this project was to develop and integrate cost-effective microcontrollers and sensors to create electronic meters or data acquisition systems and use them in multiple courses to provide students with interdisciplinary experiences to understand concepts as part of engineering systems. Each student could acquire his/her own system to use at school or at home because of cost-effective tools and open-source software. Specifically, the authors integrated and tested a hardware kit based on an inexpensive microcontroller (like a PIC or Arduino) and with different sensors. In addition, the authors developed challenges with hands-on activities for the Introduction to Engineering course, and other challenges will be developed in a similar way for courses such as Statics, Dynamics, and Mechanics of Materials. Preliminary implementation results are presented. The initial implementation was based on recommendations from students in an effort to determine in which courses it could make the best contribution and impact. Once a particular system was developed and implemented, it was relatively easy to adapt to any other similar and compatible sensor. The authors were able to perform experiments using their own portable computers connected through a USB port to a low-cost microcontroller and compatible sensors to measure temperature, light intensity, deflection, acceleration, and force, or other physical properties of interest. Positive results in student motivation were observed. Special features such as wireless communication and I2C sensors are part of an ongoing project that will be incorporated to the system in the near future and in other courses.

Introduction

Many engineering programs have been and continue to redesign their first- and second-year curriculum with strong hands-on components and/or design experiences to motivate student learning and increase student engagement and comprehension of fundamental engineering principles[3-11]. Literature shows that there is a broad agreement that a strong freshman student engagement is important for diverse student attraction, retention, and motivation. Specifically, research points to the need of emphasizing the *relevance of studies to the real word*[1] as one of the key reasons STEM students decide to drop-out or transfer out of STEM undergraduate fields. Therefore, it is important for students selecting STEM fields to be engaged and participate in activities to discover and confirm the connections, relevance, and compatibility of the classroom learning experiences and the real world – activities that they do not find in the traditional classroom environments[1,2]. At the same time, STEM professionals require not only a solid understanding of the fundamental principles and knowledge in their discipline but also they need to be able to adapt to opportunities and applications as these fields evolve. Achieving *adaptive expertise* is not trivial; it is common that people can develop advanced technical expertise in a field independently of abilities to adapt and innovate when presented with a problem in a new context[3].

Sensor networks and sensor data play a critical role in engineering and science applications such as controlling industrial processes and monitoring infrastructure and equipment[16]. The early inclusion of sensor science and sensor data within the engineering classroom is beneficial for engineering education. For example, the integration of sensors in secondary school classrooms has proven beneficial in motivating student to pursue science and engineering disciplines and career paths[17] and it also has enhanced science teaching and fostered interest to technology in K-12 schools[18]. However, when students only learn about sensors and microcontrollers in one or two junior or senior courses such as Measurement and Instrumentation and in elective courses such as Mechatronics, there seems to be a deficiency in their preparation to face challenges in undergraduate research projects, internships, and in senior design projects, in particular when the final product is expected to be a complete electromechanical or mechatronics system.

Mechatronics is a mixture of technologies and disciplines in mechanical engineering, electronics, intelligent control systems, and computer science that together can help design better and smarter products and processes. Mechatronics does not map to any particular trade or job category; rather, it refers to a host of integrated skills that can be applied in a variety of job contexts. Skills found under the mechatronics technology umbrella include “practical” knowledge in the integration of electrical systems, fluid power, electronics, computer controls, programmable logic controllers (PLCs), microcontrollers, instrumentation, robotics and information technology. With the idea of introducing mechatronics as early as possible in the engineering curriculum, Yang and Mariappan[12] created a mechatronics system installed on top of a plastic lid (of a storage box) and with a stationary model car with sensors, switches, motors, LEDs, and LCD displays in order to provide students with a setup to perform experiments and demonstrations. Also, Xu et al. created several challenges to teach the engineering design process and to use the legacy cycle in a freshmen-level robotics fundamental course in a two-year community college[13]; and, in a similar way, a six-week course for high school and community college instructors was developed and implemented. They used commercial kits such as LEGO Mindstorm and Boe-bots and also a quadrotor system to create the course modules and challenges. In another project, based on the fact that there is a lack of courses to teach sensor technology, Faradmand et al. proposed to use, in several multidisciplinary courses, a low-cost system for students to integrate sensors, such as accelerometers and temperature sensors, with LabVIEW and a data acquisition system (DAQ)[33]. The experiments were implemented in a section of second year physics and one section of first year electronics; the results were good and the response by the students to further get involved with these systems was positive; but, improvements to the modules were expected. Wireless modules, like XBees, are also used by more advanced students to perform other activities. Wagner et al. developed an elective mechatronics and materials handling systems course for students to integrate sensors, PLCs, actuators, human factors, electric power, electronics, electric motors, systems integration and controls and their applications to consumer products, specialized equipment, and manufacturing environments[14]. Sadek et al. incorporated wireless sensors in new and existing courses in four engineering disciplines and computer science, starting at a first-year engineering design course, and later in several other courses, including senior and graduate courses, and also using them in K-12 activities[15].

At present, most components of fundamental engineering courses in the design sequence at The University of Texas-Pan American such as Introduction to Engineering, Statics, Dynamics, and

Mechanics of Materials do not have laboratory sessions to assist students acquiring and validating knowledge of material presented in the lectures and in the textbooks. As a result, some students lack visualization and real life experiences about the theory studied in these courses. The main goal of this project was to develop and integrate cost-effective microcontrollers and sensors to create electronic meters or data acquisition systems and use them in multiple courses to provide students with interdisciplinary experiences to understand concepts as part of engineering systems. The goal is also to provide hands-on experiences in fundamental design engineering courses for students to obtain a more practical understanding of basic concepts and to facilitate learning difficult concepts. These experiences will help students to develop better understanding and problem solving skills. By introducing the use of sensors and interfacing them with microcontrollers and/or data acquisition systems, students gain knowledge about basic electronics, programming, engineering units and conversions, and data presentation and graphing. At the same time, they experiment measuring numerous physical parameters to get a practical understanding that assist making connections to real life situations when solving problems in different courses. These activities allow integrating knowledge and applying it to engineering systems, to complement the commonly isolated theoretical approach used to study specific concepts. Consequently, a more practical approach to involve students in the learning process is created. This paper describes the integrated low-cost hardware kit consisting of a microcontroller and several sensors used to solve several challenges with hands-on activities by following specific teamwork assignments in the courses. This paper also describes student challenges used with the tool, including an Introduction to Engineering challenge with hands-on activities, as examples of curriculum being developed in the engineering design curriculum.

Integration of Sensors and Microcontrollers

A kit consisting of microcontroller and sensors was integrated to offer a simple to assemble and easy to program option for students to perform experiments in the lab or at home. It consisted of an Arduino Uno microcontroller and sensors to measure temperature, light intensity, and deflection. Even though the microcontroller selected to read the sensors was an Arduino Uno, other microcontrollers or data acquisition systems (DAS) such as PIC microcontrollers or LabVIEW and a DAS, among others, could also be used. Arduino Uno has several advantages; for instance, it is powered by the same USB cable that it uses not only to program it but also to send collected data to the computer monitor. Successful college student construction of sensor/control networks using low-cost PIC microcontroller and Arduino development boards have been reported in the literature[15,19]. Arduino is an inexpensive, compact, open-source electronics prototyping platform, which makes it a versatile teaching tool and its broad interest has helped resolving many of the issues with the support of the hardware platform[19]. Arduino microcontrollers are affordable (i.e. less than $30), and a kit containing the microcontroller, a small breadboard, USB cable, wires, resistors, LEDs, and some sensors can be obtained for about $60 from different vendors (in 2012). The software to program the microcontroller is free[21]. The integrated system has a basic hardware configuration; however, the most important contribution of this project consists of numerous challenges which students have to solve in several topics and courses. An example of these challenges is presented in one of the next sections of this paper. After solving the challenges, the results of the sensors' measurements are presented on the screen of a portable computer or on a liquid crystal display (LCD). At present, this is an ongoing project that is continuously evolving with challenges that are being developed or adapted to different topics and courses. The implementation of this project starts in the Introduction to Engineering course, and it continues in Statics, Dynamics, and Mechanics of Solids, in which students will measure temperature, force, moment, acceleration, deflection, pressure, radius of curvature, and stress, among other parameters.

In the Introduction to Engineering course, students will complete the following parts of this project:

- Acquire a basic kit consisting of a microcontroller and some sensors to solve several challenges.
- Acquire skills and learn concepts in basic electronics such as how to use a breadboard and apply Ohm's law.
- Understand and learn basic programming commands and structures.
- Get a fundamental understanding about sensors, calibration, graphing and data presentation, and curve fitting.
- Learn about units and conversions.

A group of students helping with the project suggested creating a box for the microcontroller and sensors kit to be covered and organized and to carry and use it in the lab and at home. Figure 1 presents the proposed model of the box for the kit. This model also shows three different holes that will be used to connect the Arduino to the external power supply, computer, and sensors.

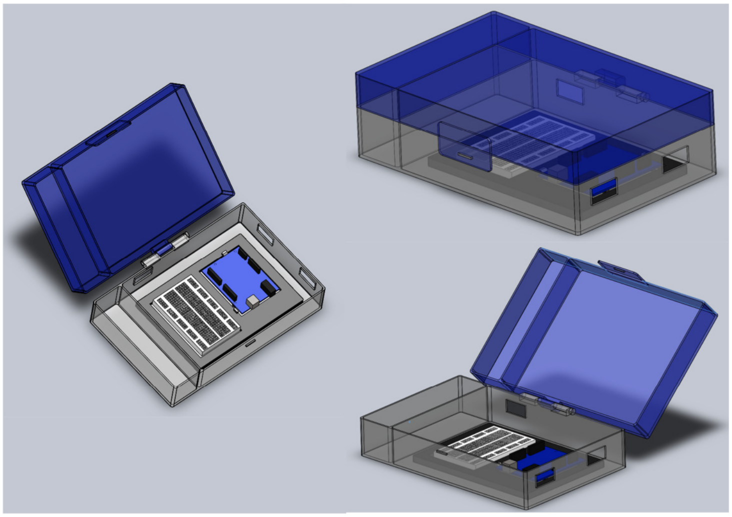

Figure 1. Box for the microcontroller and sensors kit.

Challenge-Based Instruction (CBI)

Challenge-based instruction was selected as the pedagogy to be used in this project to promote student engagement and adaptive expertise. CBI was originally developed inspired on How People Learn (HPL) and, in this project, it is implemented using the STAR legacy cycle that possesses four common dimensions: a focus on the knowledge, learner, assessment and community[22-25]. The legacy cycle, illustrated in Figure 2, contains a sequence of steps that immerses the learner in the four dimensions of the HPL effective learning environment and provides a framework for CBI and the design of associated learning activities.

Figure 2. Legacy Cycle

The legacy cycle consists of the process followed to solve challenges that are designed to motivate and engage students in learning activities. In the LC, the following steps are performed and repeated:

- Generate ideas: Students are asked to generate a list of issues and answers that they think are relevant to the challenge; to share ideas with fellow students; and to appreciate which ideas are "new" and to revise their list. ***Learner and community centered***.
- Multiple perspectives: The student is asked to elicit ideas and approaches concerning this challenge from "experts." ***Community and knowledge centered***.
- Research and revise: Reference materials to help the student reach the goals of exploring the challenge and to revise their original ideas are introduced here. ***Knowledge and learner centered***.
- Test your mettle: Summative instructional events are now presented. ***Knowledge and learner centered***.
- Go public: This step is to motivate the student to do well. ***Learner and community centered***.

The legacy cycle contains steps or activities that appeal to different learning styles and most of those activities align themselves nicely with key phases of the engineering design process. A challenge begins with an open-ended problem followed by generating ideas and questions about the challenge. Then, students encounter multiple perspectives on the issue and have the opportunity to revise their initial ideas in light of new information from lectures, handouts, and other sources. In the final phases of CBI, students test their developing understanding of the concepts targeted by the challenge before going public with a final solution or response to the challenge. As students go over these steps, the facets of knowledge-, learner-, community-, and assessment-centeredness come into play.

Student challenges that have been completed and others that will be developed using sensors for freshman and sophomore level courses, in particular for Introduction to Engineering, Statics, Dynamics, and Mechanics of Materials, include:

- Challenge 1: Measuring room temperature using a thermistor which is a variable resistor that changes as a function of temperature.
- Challenge 2: Making decisions to automatically activate street lights using a light sensor which is a variable resistor as a function of light intensity.
- Challenge 3: Use a flexion sensor to determine the radius of curvature of a mechanical component such as a wheel, ball, or disk. The flexion sensor is a variable resistor that changes as a function of the angle of deflection of a flexible strip.
- Challenge 4: Creating a scale to determine weight and mass of objects or to determine normal forces and moments (i.e. force times distance). The force sensor is a variable resistor that changes as a function of the magnitude of the force pressing against a small circular region.
- Challenge 5: Measuring position, velocity, and acceleration. Sensors such as potentiometers, tachometers, and/or accelerometers will be used to read these parameters.
- Challenge 6: Measuring strain and stress. Strain gages and force sensors will be used to measure stress.

Some of these challenges will be continued from one course to another in a progressive way to include new knowledge and concepts; for example, the sensors used to measure forces and moments in Statics will be used to measure average normal stress in Mechanics of Materials.

Sensor Challenge Example for Introduction to Engineering: Temperature Sensor

This section describes an example of a challenge that uses sensors and microcontrollers for students in the Introduction to Engineering course.

Goals

- To understand and implement a temperature sensor.
- To determine a calibration curve.
- To program a microcontroller to read voltage, convert it to temperature, and display the results on the computer monitor.

Objectives

- Understand and measure resistance and voltage.
- Understand and apply Ohm's law.
- Learn about thermistor and its calibration curve.
- Write, download, and execute a basic program on a microcontroller.
- Understand how voltage obtained from a simple electrical circuit containing a thermistor is used to measure temperature.

Challenge

The description of this challenge applies in general to any sensor that consists of a variable resistor that changes as a function of a physical parameter to be measured. Therefore, after students successfully complete the first challenge, other challenges with similar sensors are expected to be easier to complete. Student teams are formed to work together throughout the challenge and the instructor presents the first challenge as described in Figure 3.

Temperature Sensor Challenge

Some of the rooms in the engineering building seem to be at temperatures which make them uncomfortable, they are either too cold or too hot. This situation also happens at other buildings and at some student's homes. It is your job to use a temperature sensor to develop and implement a temperature measuring system in order to test our hypothesis. It is required that the temperature reading be display on the monitor of a laptop computer in degrees Fahrenheit and in degrees Celsius.

Figure 3. Temperature Sensor Challenge

The time required to implement this challenge varies depending on the type of assignments the students might progressively complete. It is convenient to achieve the objectives in a progressive and integrated manner so that the students in Introduction to Engineering obtain a final solution consisting of a complete system, that is formed by components and steps that are usually studied in separate ways. It is expected that most of the challenge activities are performed by students outside of the classroom as teamwork assignments and online assessments. The following steps and timeline are being planned for this first challenge:

- Pre-test, challenge handout, and assignment 1. This takes about 20 minutes of class time. For this task, the authors of this paper use an online pre-test and post-test using Respondus and Blackboard software packages.
- Assignment 1 consists of studying the challenge handout and completing an online assessment with questions related to the challenge in general and to basic electronic circuits including Ohm's law and circuits involving resistors and voltage sources.
- Assignment 2 consists of studying and understanding a thermistor, connecting it and determining its calibration curve required by the microcontroller to measure temperature. This activity takes about one and a half weeks to be completed and graded.
- Next, assignment 3 consists of programming the microcontroller to read voltage, use the calibration curve and display the temperature value on the screen of a laptop computer or LCD. Also, the students will measure the temperature in different rooms in the engineering building and in their houses. They will present their results to the rest of the class. This takes about two more weeks to be completed.
- A post-test is implemented online after all groups have completed the presentation of their results.

In summary, this temperature sensor challenge takes only about 30 minutes of class time and the rest is done by the students through teamwork assignments and online assessments. This challenge covers 50% or more of the material studied in the Introduction to Engineering course: graphing and data presentation, basic electronics, programming, calibration, sensors, unit conversions, engineering design process, scientific method, and oral presentations.

It is important to consider that numerous sensors consist of variable resistors which change as a function of particular physical properties such as temperature, position, deformation, deflection, pressure, among others. It is common practice to connect this type of sensor in series with a constant resistor, R_1, as shown in Figure 4, in order to create a voltage divider whose middle point voltage, V_T, varies as a function of resistor R_T, hence as a function of the physical parameter to be measured.

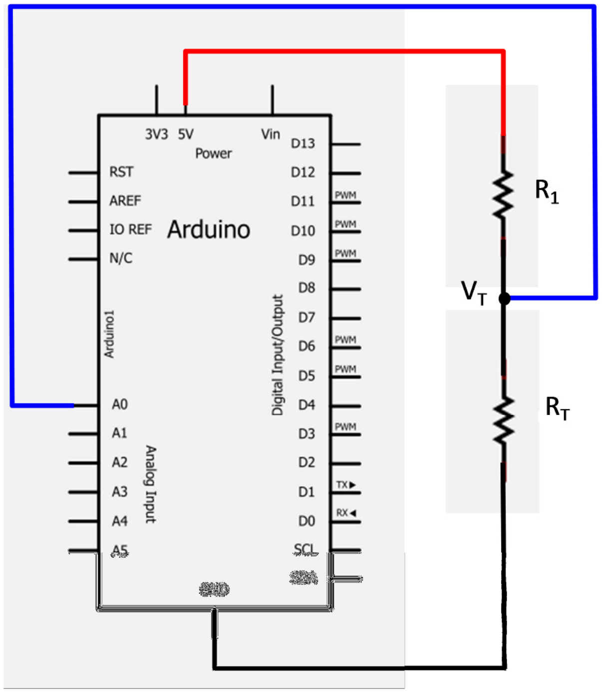

Figure 4. Arduino microcontroller and variable resistance sensor, R_T, connections[27].

In order to present schematics of the connections of the microcontroller and sensors, students are recommended to use Fritzing[27] which is an open-source software made to support designers, researchers and hobbyists in prototyping circuit boards and also to create the actual products.

A calibration curve is required to determine the relationship between the physical parameter that is being measured and the electrical property the microcontroller or data acquisition system is measuring. Figure 5 presents the calibration curve for a 10 kΩ thermistor obtained with data from the manufacturer's datasheet[26]. If the temperatures being measured are only room temperatures, the range of the calibration curve could also be limited to temperatures between 20 and 40°C, for example, and the calibration equation might be simplified to a straight line or a second order equation. These are options students might consider depending on what other temperatures they might be interested in measuring besides room temperatures; they might opt to measure the temperature of warm water, ice water, or others.

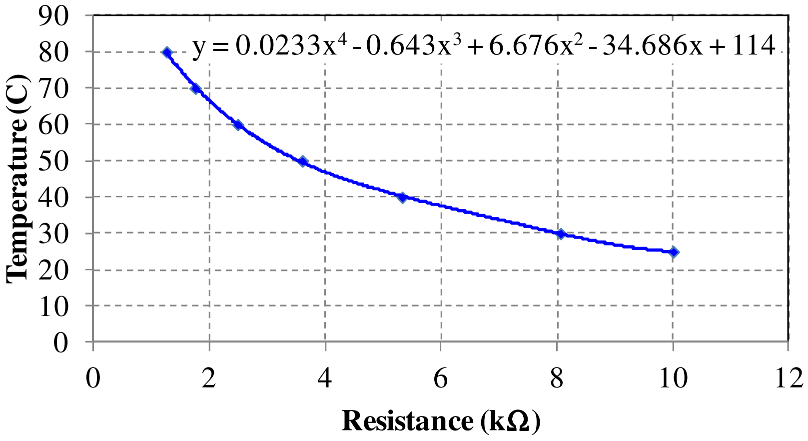

Figure 5. Calibration curve for a 10 kΩ thermistor[25].

It might also be a good idea to find the calibration curve between the digital value obtained by the 10-bit analog to digital converter of the microcontroller and the physical parameter being measured, but, this might require creating an experiment to calibrate the sensor using a thermometer as a reference. An advantage of the latter procedure is that a single equation would have to be implemented in the microcontroller code to convert the digital value to the temperature value. Otherwise, the following steps are required. First, the digital value, ADC_v, obtained by the 10-bit microcontroller has to be converted to the corresponding voltage, V_T:

$$V_T = \frac{5}{1024} ADC_v \qquad (1)$$

After that, the resistance R_T needs to be determined:

$$R_T = \frac{R_1 V_T}{5 - V_T} \qquad (2)$$

Finally, the calibration curve, like the one in Figure 5, is required to compute the physical parameter being measured.

This is an example of one of the challenges developed for the Introduction to Engineering course. In a similar way, other challenges were and are being developed for other topics and courses.

Conclusions

This paper presented the integration and initial implementation of an educational low-cost sensor tool that can be set up and used by students in and out of their engineering classes to assist their learning. The tool is based on a system that consists on an Arduino microcontroller and different sensors. The systems was connected to a portable computer through a USB port to measure physical properties of interest including temperature, light intensity, deflection, acceleration, and force. Several student challenges were developed to demonstrate how this tool could be used to help student obtain a more practical understanding of new concepts in fundamental engineering design courses. Student responses in initial implementation indicated that the majority of them found the challenges helpful in enhancing their learning. Additional work is being developed in this project to implement it with more students and assess the results. Ongoing work in this project includes adding special features such as wireless communication and I2C sensors and the expansion of the use of the tool to other engineering courses.

References

1. Collea, F. P. (1990), Increasing minorities in science and engineering, Journal of College Science Teaching, 20(1),31-34.
2. Altschuld, James W. & White, Jeffry L., Persistence of Interest in Science, Technology, Engineering, and Mathematics: A minority retention study. Journal of Women and Minorities in Science and Engineering, 2006. 12(1): p. 47-64.
3. Mascaro, D. J., Morris Bamber, S.J., Roemer, R. 2011. Spiral Laboratories I the First-Year Mechanical Engineering Curriculum. ASEE Annual Conference.
4. Calabro, K.M., et al. 3008. New Directions in Freshman Engineering Design at the University of Maryland. Frontiers in Education.
5. Freuler, R.J., et al. 2001. Developing and Implementing Hand-On Laboratory Exercises and Design Projects for First Year Engineering Students. ASEE Annual Conference.
6. Froyd, J., et al. 2005. A Project-Based Approach to First-Year Engineering Curriculum Development. ASEE Annual Conference.
7. Hall, D., Hegab, H., Nelson, J. 2008. Living with the Lab – A Freshman Curriculum to Boost Hands-On Learning, Student Confidence, and Innovation. ASEE Annual Conference.
8. Knight, D.W., Carlson, L.E., and Sullivan, J.F. 2003. Staying in Engineering: Impact of Hand-On, Team-Based, First-Year Project Course on Student Retention. ASEE Annual Conference.
9. Knight, D.W., Carlson, L.E., and Sullivan, J.F. 2007. Improving Engineering Student Retention Through Hands-On Team Based, First-Year Design Projects. International Conference on Research in Engineering Education, Honolulu, Hawaii.
10. Hall, D., et al. 2008. Living with the Lab: A Curriculum to Prepare Freshman Students to Meet the Attributes of the Engineer 2020. ASEE Annual Conference.
11. Froyd, J. E. 2011. Problem-based learning and adaptive expertise. Frontiers in Education.
12. Yang, Samuel and Jawaharlal, Mariappan. 2007. A General Purpose Sensor Board for Mechatronic Experiments. ASEE Annual Conference.
13. Xu, Yan; Yilmaz, Muhittin; Babb, Allen; and Abdelrahman, Mohamed. 2012. A Learning Module Using Engineering Design Process and Legacy Cycle for a Freshmen-level Robotic Class.
14. Wagner, John; Collins, Randy; Gramopadhye, Anand; and Shirley, Trey. 2009. A Mechatronics (and Material Handling Systems) Course: Classroom Topics, Laboratory Experiments, and Project. ASEE Annual Conference.

15. Mullet, G.J. 2012. Teaching Networked Embedded Control at the Two-Year College Level. ASEE Annual Conference.
16. Meyer, G. 2008. Instrumentation and Controls for Agricultural and Biological Engineering Students. ASEE Annual Conference.
17. Arsenault, J. et al. 2005. Integration of Sensors into Secondary School Classrooms. ASEE Annual Conference.
18. Mahonen, P.; Meshkova, E.; and Riihijarvi, J.. 2008. A Novel Partnership of a School and a University: Using the Work of University Students to Enhance Science Teaching and to Foster Interest to Technology in K-12 schools.
19. Recktenwald, G.W., and Hall, D.. 2011. Using Arduino as a Platform for Programming Design and Measurement in a Freshman Engineering Course. ASEE Annual Conference.
20. Sadek, Adel; Rizzo, Donna; Frolik, Jeff; and Sansoz, Frederic. 2007. A Multidisciplinary Curricular Effort Incorporating Wireless Sensors. ASEE Annual Conference.
21. URL: http://arduino.cc/en/Main/Software
22. Freeman, R., Vasquez, H., Fuentes, A., Knecht, M., Martin, T.; Walker, J.; Ortiz, A. 2009. Development and implementation of challenge-based instruction in statics and dynamics. ASEE Annual Conference.
23. Bransford, J. D., Brown, A. L. & Cocking, R .R. (2000). How people learn: Brain, mind, experience, and school. Washington, DC: National Academy Press.
24. Martin, T, Rivale, S. and Diller, K.R. (2007). Comparison of student learning for challenge based and traditional instruction in Biomedical Engineering. Annals of Biomedical Engineering, 35(8), 1312-1323.
25. Vasquez, H.; Fuentes, A.; and Freeman, R. 2012. Improving Student Retention and Engagement in Statics through Online Formative Assessments and Recitations.
26. URL: http://www.veris.com/docs/support/faq/RTD-Thermistor_Z202030-0N.pdf
27. URL: http://fritzing.org/
28. Pritchard, John W. and Mina, Mani. 2012. Hands-on, Discovery, Critical Thinking, and Freshman Engineering. ASEE Annual Conference.
29. Mullett, Gary J. 2012. Teaching Networked Embedded Control at the Two-year College Level. ASEE Annual Conference.
30. Madhavan, Krishna and Xian, Hanjun. 2010. Sensorworld: A New Approach to Incorporating Large Scale Sensor Data into Engineering Learning Environments. ASEE Annual Conference.
31. Ohland, Matthew; Yuhasz, Amy G.; and Stephan, Elizabeth A. 2004. The Use of Sensors in the Engineering Classroom: Design of an Educational Experiment. ASEE Annual Conference.

32. Stephan, Elizabeth A. and Ohland, Matthew. 2005. Using Real Time Sensors in the Engineering Classroom: The Ongoing Development of an Engineering Education Experiment. ASEE Annual Conference.

33. Farahmand, Farid; Kesireddy, Leela Mohan; Lynch, Mark. 2009. A Low Cost Approach to Integrating Sensor Technology in Multidisciplinary Courses. ASEE Annual Conference.

34. George Meyer. 2008. Instrumentation and Controls for Agricultural and Biological Engineering ASEE Annual Conference.

35. Yousuf, Asad and Schecklman, Tyler. 2011. Home Automation with Microcontroller and Networking. ASEE Annual Conference.