Designing and Teaching an Intensively Hands–On Course in a Large Public University

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Abstract

In Autumn 2012 the Ohio State University converted its academic calendar from a ten–week quarter system to a fifteen–week semester–based academic year. The Department of Mechanical and Aerospace Engineering (MAE) elected to take advantage of this very rare opportunity to completely re–design the mechanical engineering curriculum. Following extensive discussions with alumni, students, industry, and faculty at Ohio State and other engineering institutions, the MAE department made the decision to add a new course for students entering the department in the second semester of their second year. The course was designed to emphasize hands–on skills while exposing students to typical problems that confront mechanical engineers in industry.

This paper describes the evolution of the course as we first created a teaching platform that would be at the heart of the course. Because the thrust of the course was to quickly immerse the students in hands–on engineering, we decided to build the entire course around the shop/laboratory experience. Lectures were structured to provide 'just in time' information to the students as they fabricated, assembled, and tested the apparatus in the laboratory. The design of this 'teaching platform' was clearly a crucial part of the entire course design.

We pilot tested two versions of the course in 2011–2012, while still on the quarter calendar, and recently completed the first full semester version of the course. In this paper we present the evolution of our design thinking, the problems encountered in designing an appropriate 'teaching platform', and our experience in offering an intensive hands–on experience to almost two hundred students with widely differing levels of expertise.

Introduction: redesigning the mechanical engineering curriculum

In August 2012 the Ohio State University converted from an academic calendar based on ten–week quarters to one based on fifteen–week semesters. Three years previously, the Department of Mechanical and Aerospace Engineering (MAE) at Ohio State decided to take advantage of this academic conversion to re–design the entire mechanical engineering curriculum. Following extensive discussions with industry, alumni, students, and faculty both at Ohio State and at several of our benchmark institutions, we elected to devote a larger percentage of the curriculum to experiential learning for our undergraduates.

Three major changes resulted from this decision:

- the required capstone course in the senior year was expanded to a two–semester sequence, with several different tracks made available to students with varying interests. These tracks ranged from conventional mechanical engineering problems to motorsports, biomedical device design, product design, and an interdisciplinary design experience through the College of Engineering.

- the manufacturing processes course that traditionally was taught in the second year was moved to the senior year and totally re–designed to better fit the specific needs of mechanical engineers. The new course assumes a background in heat transfer and machine design, and emphasizes experiential learning in the lab coupled with extensive analysis and simulation of manufacturing processes.

- an entirely new course, ME 2900 "Introduction to Design in Mechanical Engineering" is now required of all students entering the major, in the second semester of the sophomore year. This course is intended to provide students with skills they will need to successfully complete subsequent design courses in the major, and to make them effective engineers more quickly when they begin their careers.

This new course for sophomore–level students entering the major is the subject of this paper. To date, we have piloted two ten–week versions of the course under the quarter calendar in 2011–2012, and have recently completed the first offering of the semester–long course to 198 students in December, 2012. We are currently teaching the second full semester course to another 160 second–year students. Our experience in preparing and teaching the course over the past two years has led to major changes in our expectations for the course, and in the structure of the course itself. This paper summarizes what we have learned to date about creating a very intensive, hands–on experience for extremely large numbers of students.

Background and motivation

The MAE Department at Ohio State, motivated by our own experience as well as reports from ASME (specifically, its Vision 2030 study[1]), the National Science Foundation (NSF), the National Academy of Engineers (NAE), and benchmark universities, made the decision to emphasize experiential learning while at the same time providing students with skills they'll need to design and build engineered systems in later years. Villanova[2] University, Georgia Tech[3], and Kettering University[4] have recently documented new sophomore–level design courses focusing on providing a broad introduction to mechanical engineering and the fabrication of a device. The University of Houston[5], Purdue University[6], University of Southern Alabama[7], Rensselaer Polytechnic Institute[8], and Virginia Polytechnic Institute and State University[9] also have sophomore level courses, but these courses focus more on the design and build process. Other schools such as Pennsylvania State University[10] and Rowan University[11] are focusing on multidisciplinary or multinational design teams. The University of Utah[12] has also addressed the challenge of large class size (a major constraint for our department) and has recently modified their curriculum to utilize more hands-on and active learning concepts with 150 students per term.

Beyond introducing mechanical engineering to entering students in an experiential context, an important secondary goal was to create a device – a ‘teaching platform’ – that would be able to integrate many facets of mechanical engineering. Like many other undergraduate programs in mechanical engineering, our curriculum is divided into four primary areas: mechanics, machine design, thermal and fluid systems, and dynamic systems and controls. In creating this new course, our intent was to show the students how these seemingly disparate parts of the curriculum mesh in practice. Thus the need to create a platform that was rich enough to support its integration in later courses over the remaining four semesters, yet broad enough to span the entire discipline.

The compressed air motor is an ideal choice for several reasons. First, it allows us to introduce thermodynamic concepts very early, and link them directly to energy, force, and torque. We quickly move to machine design and machine components, emphasize the importance of precision, and show how precision is attained in the machine shop. We explicitly draw the connection between the datum surfaces in the CAD designs the students create, the datum surfaces on our machine tools, and how students must take these factors into account in order to preserve design intent.

The motor is also an ideal choice for introducing basic control concepts, such as open-loop and closed–loop control. Students learn to program a small microprocessor, and use it to control the flow of air to their motor. Finally, testing the motor on a dynamometer at the end of the semester allows us to give the students a very brief introduction to the problems associated with data acquisition. The course syllabus is quite ambitious, but it achieves our goal of giving the students a broad introduction to our discipline.

Course Constraints

The overriding goal of this course is to introduce second–year students to hands–on skills that they will need to be successful engineering designers, both in subsequent courses and most especially, out on the job. This entails a need to provide extensive experience in the machine shop, the CAD studio, and the electronics laboratory. At Ohio State, given the large number of students who currently enroll in the major, our primary constraint in the design of this course was providing a truly rich experience for our students while also coping with burgeoning enrollments and shrinking resources.

The undergraduate mechanical engineering program at the Ohio State University is one of the largest in the country. Over the past seven years, the program has seen a significant increase in enrollment, from 865 undergraduates in 2005 to 1337 in 2012. The program in mechanical engineering is now the largest undergraduate major in the College of

Engineering at Ohio State, and is one of the largest is the United States. In total, our department now serves almost 1800 pre–major, major, and graduate students in mechanical engineering, aeronautical engineering, and nuclear engineering programs. In planning a new course that relies so heavily on experiential learning, the primary constraint was simply finding a way to move large numbers of students through a structured set of exercises while maximizing the pedagogical benefit to the student.

Autumn 2011: the first pilot course

In early Spring, 2011, the decision was made to offer two pilot versions of the new course during the 2011–2012 academic year. Given that our academic quarters were only ten weeks long, it was not possible to pilot an entire semester–length course in a single quarter without greatly increasing the number of hours students would spend in class. Our original solution was to offer two distinct pilot courses: the first, offered in Autumn 2011, would emphasize the machine shop aspects of the course; the second, following in Winter 2012, would require less time in the machine shop, but much more time working in the electronics lab with the Arduino© microprocessor.

In Autumn Quarter, 2011, we launched the first pilot course with a group of second and third–year students, all of whom volunteered to take the class as a technical elective. In the spring of 2011 we visited several second–year mechanical engineering classes to alert students that these pilots would be offered in the 2011–2012 academic year. We followed that up with an evening recruitment event in late spring, and succeeded in recruiting 26 second–year students for the first pilot. Of the 26 students, five were female and one was Hispanic. Sixteen students had completed the first year honors engineering program before entering the department, nine went through the standard first year engineering program, and one student transferred from another university.

From the beginning, our intent was that the course would be built around a fairly complex device that the students would construct and test. Students would attend two 1.5 hour lectures per week, in addition to a two–hour lab period, which would be spent in either the machine shop or the electronics lab. Lectures would be structured to provide needed information 'just in time' for students to apply it in the shop or lab. Our belief was, and continues to be, that by immediately applying lecture material, students will internalize and retain material more effectively.

Our first task was to decide on a suitable teaching platform, i.e, the mechanical device that the students would construct and test. Because of the centrality of this device to the course, this decision was not an easy one. Clearly, the device had to be simple enough to be constructed by second–year students with very limited hands–on skills. At the same time, it needed to be complex enough to satisfy our requirements. In summary, the device needed to:

- Challenge students to develop real proficiency in using the machine shop and electronics lab;
- Offer interesting control scenarios, the better to integrate with the microprocessor;

- Provide a rich enough experience to cover a wide range of mechanical engineering problems;
- Integrate well with subsequent courses in the curriculum.

After much discussion, and based on our review of the literature, we elected to have the students work in teams to fabricate a fairly complex inline two–cylinder compressed air motor, shown in Figure 1. The idea for using a compressed air motor as the 'teaching platform' came from similar projects at the US Coast Guard Academy and at Cornell University. While researching several air motor designs, we discovered that a group of students in our own program had designed and built a two–cylinder version of a motor for their capstone project during the previous year. This motor became the basis of our new design.

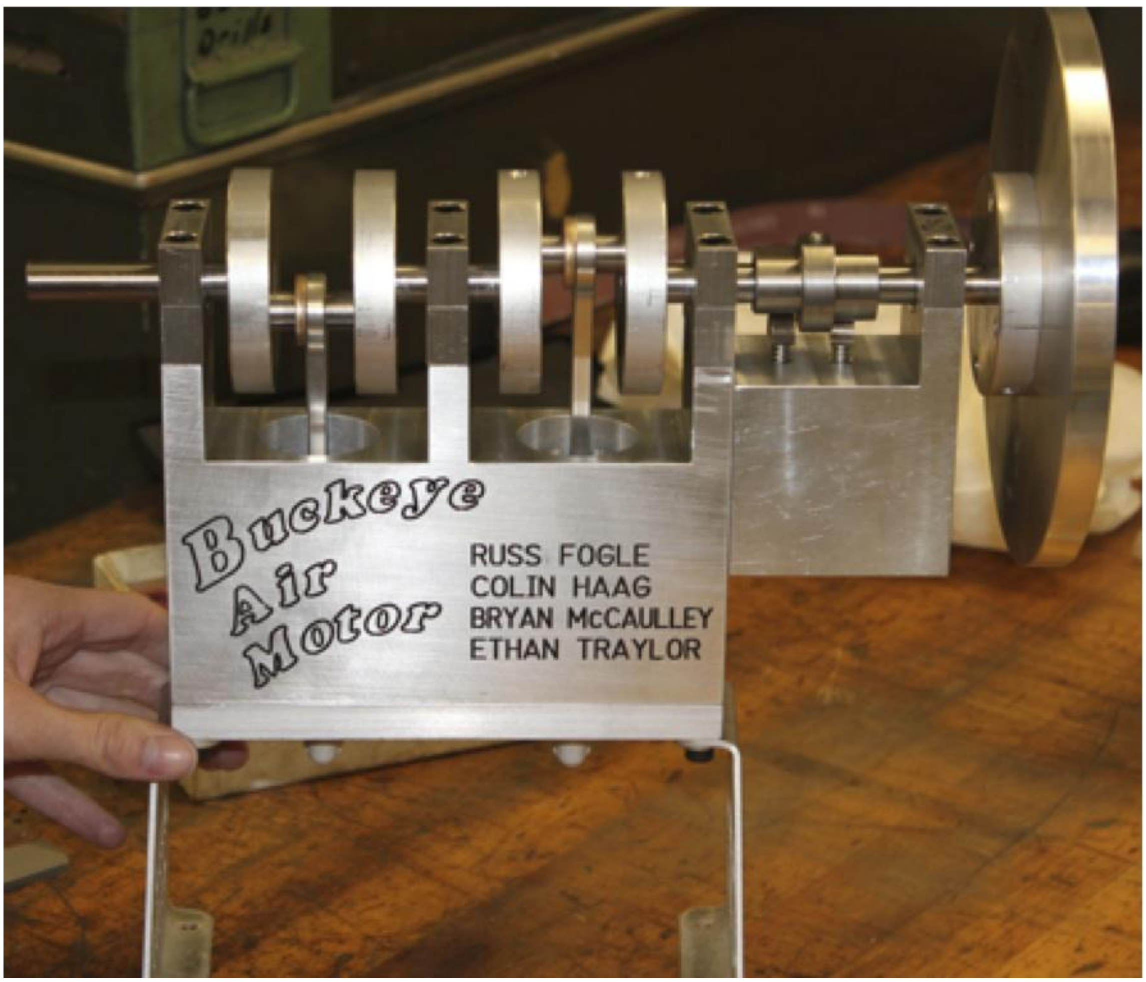

Figure 1: The first iteration of the air motor design. This two–cylinder motor requires a dual–lobe cam and followers to control air flow, and has over thirty separate components; most of which are machined by the students.

During summer 2011, a M.S. student in our program, working closely with the machine shop supervisor, re–designed the original motor to create a more robust design that was also more challenging to fabricate. This motor became the prototype for the first pilot class[13]. The motor was assembled from over thirty separate components, most of which were machined on lathes and milling machines by the students. The tolerances required for robust performance were considerable, but the students were able to machine parts from aluminum, bronze, and steel to the required tolerance levels. In this version of the motor, the flow of air to the cylinders is controlled by a cam and valves; because cam timing was crucial, it was necessary to machine the cam on a CNC milling machine. This was the only component that the students did not machine themselves.

Much tuning and tweaking of the motors was necessary to achieve optimal performance, but by the end of the first quarter all of the student teams succeeded in building fully functioning motors. One very clear result of this effort was the sense of accomplishment felt by the students. They put in long hours outside of class, and were frankly surprised when their efforts resulted in success. Another result was also quickly apparent: this initial design of the motor, while fulfilling for the students, was simply too complex to undertake given the large number of students who would be enrolled in the course in Autumn, 2012. With over thirty separate components, and with the level of finesse needed to successfully assemble the motor, it was clear that this design simply would not be feasible for the scaled–up version of the course.

In addition, it was still not clear to us how to incorporate the Arduino© microprocessor into the design of the motor. Our initial thought was that the student teams would independently design a 'mechanical load' which would be driven by the air motor, with the load controlled by the Arduino©. However, after finishing the first pilot, and coming to grips with how many hours were required for the students to become proficient at machining, we realized that it would be impractical for the students to attempt any project in the machine shop that was not highly structured. We simply do not have the resources, either in staff or in the physical plant, to support over two hundred students working simultaneously on independent designs.

By the end of Autumn Quarter, 2011, we realized that many of our initial goals for the course were not realistic. While we remained enthusiastic about having the students fabricate and assemble an air motor, it was clear that we needed a much simpler motor design that would better incorporate the Arduino© microprocessor, and thus eliminate the need for a cam and valve system.

Winter 2012: second pilot course

With the completion of the first pilot in December, 2011, we stepped back and re–evaluated the assumptions we had been working under for much of the previous year. This process led to a total re–thinking of the course objectives, and a re–ordering of the course constraints. It was clear that our original idea of following the air motor project with a more open–ended design/build experience was totally impractical, given the number of students who would be taking the class. It was also clear that the cost of running this course could be a strong disincentive to its continuation, unless we were able to find ways to reduce the costs.

With this in mind, we arrived at a new set of constraints to guide the further development of the course:

- A less complex motor design, probably by eliminating the need for a cam;
- Better integration between the motor and the microcontroller;
- A more flexible teaching platform that could easily accommodate various numbers of students working together.

As we were finishing the first pilot, the department's electronics technician, who had become intrigued with our course, independently created a very small replica of the WWII–vintage Wright Cyclone radial engine. We were able to quickly adapt this design during the month of December, and have it ready for the second pilot course, which began in January, 2012. While the first version of the motor required that all of the components be in place before it would function correctly, the radial design gave us much more flexibility in this regard.

Although all of the teams in the initial pilot were able to complete their motors on time, it was clear that we would need to plan for the inevitable situation in which some members of a team did not finish. The first version of the air motor was not at all flexible in this regard: it simply would not run unless it was complete. The new radial design, however, could be constructed to operate with any number of cylinders, from one to the maximum – we decided on six cylinders. With this design, each team member would be responsible for completing a single cylinder sub–assembly (cylinder block and cap, piston, and connecting rod). These four components ensured that every student would need to become proficient at operating the milling machine, the lathe, various hand tools, and precision measurement. If a student did not finish his or her assembly, the remainder of the team would still have a functioning motor, and the student's failure to finish would be quite obvious – a major incentive for students to keep up.

This design is also better at accommodating the large number of students involved, as it allows six students to assemble a single motor, which reduces the cost of running the course considerably. Figure 2 shows the six–cylinder version of the radial motor. The frames on which the cylinders are assembled are fabricated by our shop personnel and provided to the students; each student then assembles his or her cylinder sub–assembly to the team's frame. This design also reduces the number of solenoid valves needed for the class, which in fact are the most expensive component of the motor. Each team assembles their motor on a common frame, and then attaches the frame to one of nine test rigs which contain a microprocessor and twelve solenoids, along with the required air lines. Each student must then show that the code they have devised will run the motor as required.

Currently Arduino© microprocessors are used to control the solenoid valves which send air to each cylinder. The Arduino© concept was originally developed at the Interaction Design Institute Ivrea, in Italy, to teach design and engineering students how to program a relatively simple but sophisticated microprocessor[14]. These devices have evolved into an extremely useful tool for students, designers, and engineers looking for a low–cost but capable controller, and are extremely popular among the ‘maker’ community. Quite an extensive global user community has evolved around these devices, and considerable resources are available for students online. For this course, each student is required to purchase an Arduino© kit rather than an expensive textbook. The kit includes the basic microprocessor, as well as a prototyping breadboard and various electronic components. Students spend roughly half of the semester in the electronics lab, learning to program the microprocessor and use it with various sensors and actuators. Each student is then required to write and test their own version of code for controlling the flow of air to the assembled motor.

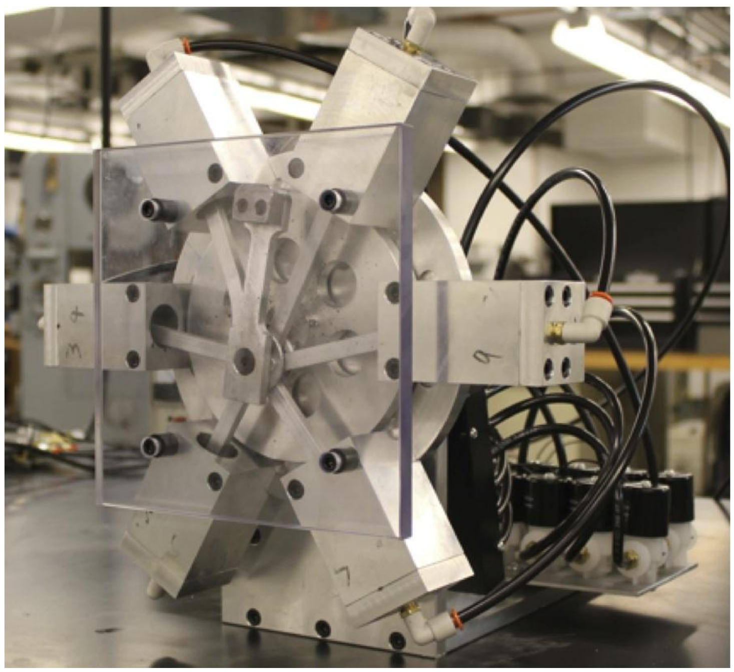

Figure 2: The second iteration has far fewer unique parts, with air flow controlled by an Arduino microprocessor and solenoid valves.

The primary disadvantage in simplifying the motor design was a diminished machine shop experience for the students, compared with our original intent. While they still spend several hours with vertical milling machines, lathes, and associated measuring devices, there’s no question that the students who were involved with the first pilot course received better training in the machine shop than did the students in subsequent offerings. On the other hand, the initial motor design did not integrate at all with the Arduino© microprocessor, and would have required a follow–on project to provide this experience. On balance, the second design which requires the use of the Arduino© board to time and regulate the flow of air to each cylinder is a much better match with the overall course objectives.

The semester version of the course

We are now in our second full semester of teaching the course, and can report that it has to this point largely met or exceeded our expectations, in terms of the course itself. The large number of students in the course, combined with our limited shop resources, mandate that we teach the course in two sections, each of approximately one hundred students. One section begins each semester in the machine shop by fabricating the motor. The supporting lectures cover an introduction to motor design, the basics of milling and turning, precision measurement, engineering materials, and machine components. The second section begins by learning to program the Arduino©, and is also presented with lectures on sensors and actuators, data acquisition, and basic electronic circuits. Both sections also have lectures on technical writing and professional presentations, and students are required to prepare and present short presentations about their experience in the course.

At the midpoint of each semester, students in the first section assemble their motors to the frames, and then move on to the electronics lab. Their motors will be tested using their own Arduino© code at the end of the semester. These students proceed with the second half of the course, in which they learn to program and apply the microprocessor to the machines they have built. The second section moves to the machine shop, and begin to fabricate their motors. By the end of the semester, both groups will have built motors and written software to drive them. Because it is impractical to include an open–ended design problem in the machine shop, we have incorporated it into the electronics section of the course. Students can choose from a variety of sensors and actuators, and then prototype a simple device, using the microprocessor, to solve a task of their own choosing.

Because the course is so different from every other course in the curriculum, we have devised our own evaluation instruments to ask specific questions about every aspect of the course. Student feedback on the course has been overwhelmingly positive. A very substantial majority of students indicate that it has been their favorite course at the university to date; many of them express surprise that they were able to learn to program a microprocessor and to machine metal to very close tolerances. Several students have indicated that they expected to dislike the programming aspect of the course in particular, and were quite surprised to find that they enjoyed it. The course clearly seems to have achieved one of its goals, to increase students' self–confidence. We have noticed this effect most clearly among our female students, almost all of whom find that they enjoy the experience, and many of whom now work as undergraduate teaching assistants in the machine shop and the electronics lab.

At the end of each term we have held an 'open house' for the students and their families, as well as for our faculty colleagues and alumni. These events have been very well attended, and have met with an enthusiastic response from all parties involved. At the conclusion of the first full semester we assembled all thirty–three of the air motors, each of which had the names of the students in each team engraved on the cylinder blocks.

Some of these motors are shown in Figure 3. The students and their guests were quite impressed to see all thirty–three motors lined up side by side. On another note, this course has been quite effective as a fundraising tool with our alumni. Many of our alumni have pursued careers in manufacturing industries, and their response to the course has been extremely positive; in several cases, their enthusiasm has been matched by generous donations to our curriculum fund, which has enabled us to purchase new equipment for the students to use in the course.

Figure 3: Some of the thirty–three air motors completed during Autumn Semester, 2012

One goal that clearly has not yet been achieved is integrating this course into the remainder of the curriculum. To be frank, many of our colleagues have been skeptical about the intent and goals of the course, and have been taking a ‘wait and see’ attitude toward it. Some of our colleagues do not see any reason to include experiential learning into the curriculum, while others question the expense of offering such a course. Indeed, were it not for a considerable fund raising effort on the part of the Department Chair, the course would not have come to fruition. Nevertheless, we hope to convince the skeptics with the continued success of the course, and in time we expect to see our air motors more fully integrated into the curriculum.

Acknowledgements

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References

1. Danielson, Scott, et al., "Vision 2030: Mechanical Engineering Education", ASME, New York, 2013.

2. Clayton, Garrett, et al. "Introduction to Mechanical Engineering - A Hands-On Approach." 2010 Annual ASEE Conference. 2010. AC 2010-1048.

3. Vaughan, Joshua, et al. "Using mechatronics to teach mechanical design and technical communication." Mechatronics (2008): 179-186.

4. Hargrove, Jeffrey B. "Curriculum, equipment and student project outcomes for mechatronics education in the core mechanical engineering program at Kettering University." Mechatronics (2002): 343-356.

5. Bannerot, Richard. "Hands-on Projects in an Early Design Course." ASEE Annual Conference and Exposition. Pittsburgh, PA, 2008.

6. Starkey, John M., et al. "Experiences in the Integration of Design Across the Mechanical Engineering Curriculum." 1994 Frontiers in Education Conference. 1994. 464-468.

7. Tsang, Edmund and Andrew Wilheim. "Integrating Materials, Manufacturing and Design in The Sophomore Year." Proceedings of the Frontiers in Education Conference. Atlanta, GA, 1995. Session 3c4.

8. Gabiele, Gary A., et al. "Product Design and Innovation: Combining the Social Sciences, Design, and Engineering." American Society for Engineering Education Annual Conference & Exposition. Salt Lake City, UT, 2004.

9. Spangler, Dewey and Kimberly Filer. "Implementation of Tablet PC Technology in ME 2024 Engineering Desing and Economics at Virginia Tech." 2008 Annual ASEE Conference & Exposition. Pittsbugh, PA, 2008.

10. Bilen, Sven G., Richard F. Devon and Gul E. Okudan. "Cumulative Knowledge and the Teaching of Engineering Design Processes." ASEE Annual Conference. Montreal, Quebec, Canada, June 16 - June 19, 2002. Session 2325.

11. Newell, James A., et al. "Multidisciplinary Design and Communication: a Pedagogical Vision." International Journal of Engineering Education (1999): 376-382.

12. Roemer, Robert, et al. "A SPIRAL Learning Curriculum in Mechanical Engineering." The 117th Annual Conference of the American Society for Engineering Education. Louisville, KY, 2010. AC 2010-1903.

13. Lu, Angelica. Prototyping a Design and Fabrication Experience for Sophomores in Mechanical Engineering. 2011. M.S. Thesis, Ohio State University, Columbus, OH.

14. http://www.arduino.cc/ Accessed 4 February 2013