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Revitalization of an Intro to ME Course Using an Arduino-Controlled Potato Cannon

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Amongst their required courses in calculus, chemistry and the humanities, most freshmen engineering students take part in some form of "Intro to Engineering" course that describes their chosen field of study through labs and demonstrations designed to motivate students and promote basic engineering skill sets[1-3]. The literature contains many studies of first year programs in engineering which show that well designed introductory engineering courses can boost student confidence and interest in engineering, resulting in significant increases in retention[4-10]. As the importance of first year engineering programs have become more widely appreciated by educators, numerous universities have recast their curricula offering "cornerstone design" courses, some of which bear up to 3 credit hours for both semesters of the freshman year[14-17]. While it is undeniable that these courses have a positive effect on students, it must also be recognized that the implementation of cornerstone projects in the curriculum is costly in terms of faculty time, and departmental resources, making full blown adaptation of this approach unattractive for many engineering schools[11-12]. In a 2005 survey of first year programs Wankat and Brannan reported that Introduction to Engineering courses averaged 1.6 credits, and that only 21.9% of the engineering schools surveyed had 2-semester intro to engineering courses[18]. These statistics suggest that even with today's emphasis on first year programs in engineering the majority of engineering schools still depend on one or two credit, single semester, introductory courses. The lack of prestige for professors associated with one credit introductory courses, as well as the small effect on student GPA, leads to a situation where these courses become outdated and irrelevant to the educational needs of the students[13].

At the Virginia Military Institute, the 1 credit hour Introduction to Mechanical Engineering course, ME-105, had reached a point where it was of limited value to students, providing some background in manufacturing and design, but no information about the increasingly important areas of programming and electromechanical systems. Despite the fact that only one credit hour was available to introduce these topics, successes at other engineering schools using Arduino Microcontrollers for short duration electro-mechanical design projects showed that it was possible provide students with a meaningful educational experience involving programming and electromechanical systems[19-22]. Starting in the fall of 2015, the Mechanical Engineering Dept. at the Virginia Military Institute, completely over hauled its ME-105 course in order to provide students with relevant experiences in the areas of:

- Machine shop practices/Fabrication
- Electro-mechanical actuators
- Computer Programming
- Mechanical Design

The centerpiece of the new Intro to ME curriculum is a 9 week lab sequence in which students build a small bore pneumatic powered potato gun that is controlled using an Arduino microcontroller. In the initial 3 weeks of the course, students learn to use the machine shop to fabricate the potato gun components. In the next four weeks, students are introduced to the Arduino microcontroller and use it to control a solenoid piloted pneumatic valve, (used to fire the

gun), as well as a stepper motor, (used to adjust the angular position of the gun). Finally, in the last 2 weeks of this project, students integrate the electrical and mechanical components, along with a firing control program to operate the gun. While potato cannons are undeniably fun for students, the sequence of labs defined for the project has the more important benefit of creating a "hands-on" perspective from which to scaffold the abstract analytical material students will be exposed to as they progress through the mechanical engineering curriculum.

In this paper the authors will provide a detailed description of the lab sequence, emphasizing the skill sets developed over each part of the project. In addition, the results of a self-assessed skill-set inventory administered to students before starting the potato cannon project and then again at the end of the course will be discussed to show how the lab sequence influenced students' beliefs about their capabilities in the area of mechanical design, electronics, and programming.

Background

Prior to the introduction of the Arduino controlled potato cannon project in ME-105, the course included a total of 6 labs spread over 11 weeks that designed to survey the Mechanical Engineering Major:

Intro and Honor Court	Describes class procedures and the requirements of the Honor Court	1 wk
GPA management	Instructed students on academic standards and time management	1wk
Machine Shop Safety	Instructed students on safety practices in the shop	1wk
Thread Gage Project Introduction	Described the fabrication of a thread gage which was performed by students outside of class time under supervision of the departmental machinist.	1 wk
Engine Tear Down Lab	Basic introduction to thermodynamic concepts/mechanical dissection of a 3.5 hp engine	2 wk
Rocket Lab	Used basic thermodynamic principles to predict the height that a model rocket would reach	2 wk
Lego Clock	Introduced machine design concepts by having students use the Lego Mind Storms system to build clocks based on gear trains made from Legos	2 wk
Leaf Blower Powered Hovercraft	Open ended design project that challenged the students to create hover crafts from leaf blowers and other basic supplies	3 wk
Welding Lab	Introduced students to welding	1 wk

In addition, three weeks of the course were consumed by lectures covering the policies of the Mechanical Engineering department and the university in general. Surveys of students from the course showed a strong preference of students that remained in mechanical engineering after their freshman year, for the labs involving design projects such as the Hover Craft and the Lego Clock, as opposed to more procedural labs like the rocket lab or engine lab[23]. The influence of

these early experiences in mechanical design can be seen clearly as students progress through the ME curriculum into courses such as statics, solid mechanics and mechanical design. At each stage in the curriculum students add to the foundation of design and fabrication experiences established in the ME-105 class, increasing their confidence and feelings of mastery in the area of mechanical design, such that by the time they graduate students have become quite competent in the practice of machine design.

While the intro course seemed to serve the purpose of encouraging students in the areas of mechanical design and fabrication, it did nothing to build student interest in the rapidly growing field of electromechanical systems. Courses that students take in the related areas of Mat lab Programming, Physics, Circuits, Instrumentation and Controls are traditionally weak areas, and in many cases they do not understand how these courses apply to mechanical engineering. In their senior year students take a mechanical design course which introduces mechatronics concepts by having students design and build an Arduino controlled can crushing mechanism[24]. It is at this point where students start to make connections between courses like programming and circuits, and how they actually apply to the domain of mechanical engineers. Interestingly, students in the machine design course often make comments such as:

> "Why couldn't we have learned programming by using the Arduino to control motors instead of writing integration functions?"
>
> "I would have understood control systems better if we'd actually built a controller"
>
> "We need to do this in circuits class"

Clearly the skills necessary to work on mechatronics projects at the senior level, required priming at the earliest level of the mechanical engineering program. Following from the success of design and fabrication projects in ME-105, it was decided to rework this course to include a lab sequence in which an Arduino controlled potato cannon is built from basic components such as stepper motors and pneumatic valves. This relatively simple electromechanical systems project serves as a means to introduce students to basic programming concepts, electronics, actuators, and mechanical fabrication during their first semester at the Virginia Military Institute, giving students the context and confidence to excel in follow on courses and projects.

Description of the Potato Cannon Lab

The purpose of the potato cannon project was to have teams of 3-4 students each,(limited equipment precluded smaller teams, although teams of 2 students each would be optimal), build a ½" bore, pneumatically powered potato cannon aimed and fired using push buttons interfaced to an Arduino microcontroller. The potato cannon lab consists of 4 modules spanning a total of 9

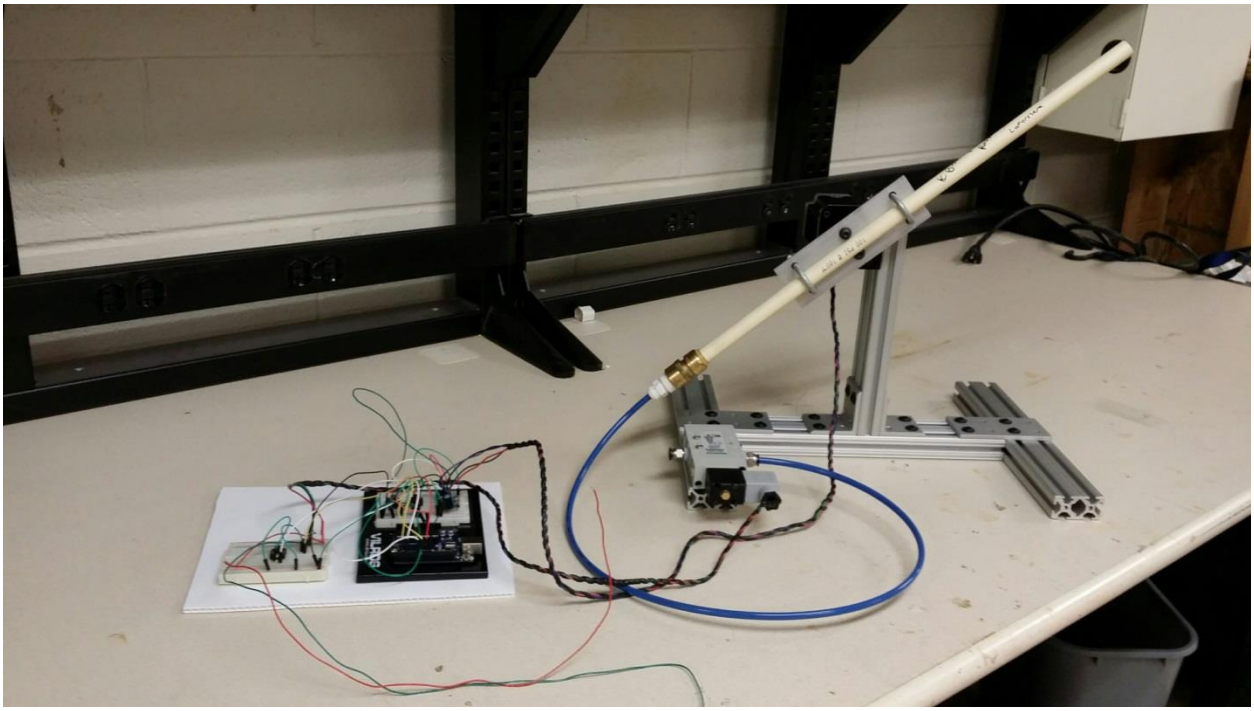

Figure 1) Arduino Controlled Potato Cannon

weeks, resulting in the elimination of the engine dissection lab, the rocket lab, and the Lego-Clock lab that were originally part of the ME-105 intro to engineering course.

Intro and Honor Court		1wk
GPA Management		1wk
Potato Cannon Module 1) Manufacturing the Stepper Motor to Cannon Barrel adapter	Introduced students to shop safety practices, milling, drilling, reaming and tapping	3wk
Potato Cannon Module 2) Arduino control of a pneumatic valve	Introduced students to the Arduino and using the Arduino to operate a solenoid driven pneumatic valve.	2 wk
Potato Cannon Module 3) Stepper Motors	Introduced students to stepper motors and used the Arduino to control the stepper motor	2 wk
Potato Cannon Module 4) Integration and Test	Assembled potato cannon mechanical components Combined stepper motor driver and pneumatic driver.	2 wk
Hover Craft Project		3 wk

Module 1: In the first module of the potato cannon project, students were given a specification for the project as well as drawings for the components of the cannon that they would be manufacturing. The specific deliverable for the first module of the potato cannon project was to have each student manufacture an adapter piece that connects the potato gun barrel to the shaft of the stepper motor used to adjust the elevation angle of the gun. Milling, drilling, reaming and tapping were all required to create the adapter piece. Over the span of 3 weeks students each student in the lab created their own adapter under the supervision of the Mechanical Engineering department machinist. In addition to gaining basic machining skills, students also learned about important design concepts such as tolerancing and assembly clearances.

Module 2: In this module, student teams were issued the Arduino Starter Kit that they would use for the remainder of the course, and given an introductory lecture on creating and executing programs on the Arduino. No prior knowledge of digital electronics or microcontrollers was assumed, and every effort was made to make the lecture more of a conversation with students so as to increase their comfort level with the new material. After having the students write their first program, (program turns on and off an LED for a prescribed amount of time), students were given instructions on how to build a simple driver circuit based on MOSFET transistors to switch and on off a solenoid piloted pneumatic valve. Students were given step by step instructions on how to wire up the driver circuit, and great care was taken to provide them with mechanical analogies to the electrical components used in order to promote qualitative understanding of the driver circuit. Granted, no attempt was made to provide mathematical descriptions of the electrical circuits, but the qualitative understanding of the circuits that students developed in this module will provide scaffolding for more rigorous treatment of circuits that they receive in subsequent courses. Students were then given a program that interfaced with the driver circuit that allowed the Arduino to open the pneumatic valve for one second every time a pushbutton is pressed. Instructors used this program to further explain the structural elements of programs written for the Arduino. Initializing variables, declaring a variable as digital input or output, along with basic conditional statements were described in the context of this program. Students were then asked to create a slight modification of the program to allow for different valve opening times. Obviously, students are not achieving mastery of either the electronics or the computer programming skills that are presented here. They are however becoming familiar with the tools of the trade, and building excitement about those tools. At the conclusion of the second week of module 2, students connected the barrels of their potato cannons to the pneumatic valve they just interfaced to the Arduino, and fired their cannons for the first time via a computer interface. The ability fire small chunks of potato at high speed from a device that they just built using computers and newly introduced electronic devices, is at once pure entertainment and the enticement to learn more.

Module 3: The goal of the third module was to use the Arduino to control the motion of the stepper motor that adjusts the elevation angle of the potato cannon. For the purposes of this lab a

NEMA 23 motor frame was used in conjunction with a DRV 1825 stepper motor driver from Pololu. At the beginning of the module, brief lectures were provided on the basic operation of stepper motors, as well as a description of the functioning of the pins on the driver chip. As in the second module, sample programs were provided to run a demonstration of stepper motor control. Instructors reviewed the code showing students how to use iteration and functions within the Arduino programming environment. Students were then asked to modify the programs so that push button inputs could be used to control the motor angle. Specifically, two push buttons were wired into the Arduino, one of which caused the motor to step counter clockwise when pressed and the other which caused the motor to step clockwise when depressed. The relative complexity of wiring the stepper motor driver chip and the push buttons simultaneously proved to make debugging of circuitry in this module much more difficult than for the pneumatic valve module. Bad connectors on wires and faulty solder joints on some of the driver boards proved frustrating to students and required instructors to figure out the problems. Nonetheless students did get to model debugging skills from their instructors and as the module progressed they were able to identify simple faults in many cases.

Module 4: In the final module of potato cannon project, students assembled the mechanical components of the potato gun, and combined the pneumatic valve driver circuitry with the stepper motor circuitry to create the finished potato cannon system. The frame of the potato cannon was created from 2” x 1” aluminum T-slot framing, pre-cut and kitted to save time. Students built up the frame, mounted the stepper motor using a pre-manufactured mounting bracket to the frame, and then mounted the adapter they manufactured to the stepper motor shaft with a setscrew. The mechanical piece of the cannon was completed by bolting the cannon barrel onto the student manufactured adapter block, and then bolting the pneumatic valve onto the T-slot framing. After several weeks of working with electronics, students enjoyed the change of pace in working on the mechanical assembly of the potato cannon, and were particularly impressed with the ease of fabrication afforded by the T-slot framing. Once the mechanical components of the potato gun were completed, students worked to integrate the electronics with potato gun. Since none of the circuits created in module 2 or module 3 were disassembled, it was a relatively easy matter to connect the pneumatic valve and stepper motors to their respective driver circuits. Originally it was intended to have students create the final program that controlled the aiming and firing of the potato cannon by cutting and pasting the various parts of programs they had already worked with in modules 2 and 3. Unfortunately, by the time physical and electrical integration tasks were completed there was not enough time left over for students to develop their own program, and still test the devices. It was decided for this first pass through the potato cannon project, the control program would be given to the students. In the future, an additional week will be added to the schedule, possibly thorough the elimination of the GPA management lecture, in which the students will be given the entire lab period to write their control program. Following completion of the potato cannon final integration, each team took part in a marksmanship competition with teams firing their potato cannons at a distance of 60ft

from the target. While firing accuracy had much more to do with shape of the potato slugs fired from the cannons than from any aiming strategies implemented by the students, the competition was an indispensable part of the project, finishing the project off with fun and leaving the students with positive associations about their first experience working with electromechanical systems.

Effects of the Arduino Controlled Potato Cannon Project

Prior to beginning the 9 week potato cannon project, a 4 question pre-project assessment was given to the students in the ME-105 class to determine how they would assess their skills in the areas of mechanical design, fabrication, electronics and computer programming using a Likert scale. The questions are reproduced below, and it can be seen that a 1 on the Likert scale indicates that the student felt he or she had little skill in a particular area, while a 5 would signify the student believes that he or she has excellent skills.

1. *How would you rate your knowledge of mechanical design on a scale of 1-5 with 1 being little or no knowledge of mechanical design and 5 signifying that you are confident in your abilities to design a mechanical system?*

   1 2 3 4 5

2. *How would you rate your fabrication skills on a scale of 1-5 with 1 signifying that you have no fabrication skills, and 5 signifying that you are well versed in building things.*

   1 2 3 4 5

3. *How would rate your knowledge of electronics and electromechanical devices on a scale of 1-5 with 1 signifying that you have no knowledge of electronics and 5 signifying that you are confident in your ability to work with electronics and electromechanical devices.*

   1 2 3 4 5

4. *How would you rate your knowledge of computer programming on a scale of 1-5 with 1 signifying that you have no programming skills and 5 signifying that you are confident in your ability to write simple computer programs*

   1 2 3 4 5

At the conclusion of the project, students were given a post-project assessment which included the same four questions concerning students' self assessed skill levels in the areas of mechanical design, fabrication, electronics and computer programming, plus one additional question to gage students' interest in working on electromechanical design projects in the future:

5. *Did the potato cannon project motivate you to want to work on more electro-mechanical design projects? Record your answer on a scale of 1-5 where 1 signifies that you would rather not deal with electro-mechanical project if at all possible in the future, and 5 represents that you would enthusiastically take part in electro-mechanical design projects in the future.*

1 2 3 4 5

Self-Assessed Mechanical Design Skills:

As shown in figure 2, more than half of the 52 students surveyed in this study reported self assessed mechanical design skills of 2 or less on the Likert Scale, indicating low confidence in their mechanical design capabilities. The average mechanical design score for the entire class was 2.44 at the pre-assessment phase. While students did not develop their own designs of the potato cannon because of limited time, they did learn many things about mechanical design ranging from why lock washers are used, to designations for common bolts and tolerancing, as they worked through the project. At the conclusion of the project student confidence in their mechanical design skills was bolstered significantly with over 90% of the class reporting scores greater than a 3 as shown in figure 3. The average mechanical design score measured by the post-assessment was 3.91, an increase of 1.47 points over the span of the project. The apparent change in student confidence level relative to mechanical design is statistically significant with $p < .001$ obtained from a one tailed paired T-test based on the survey data.

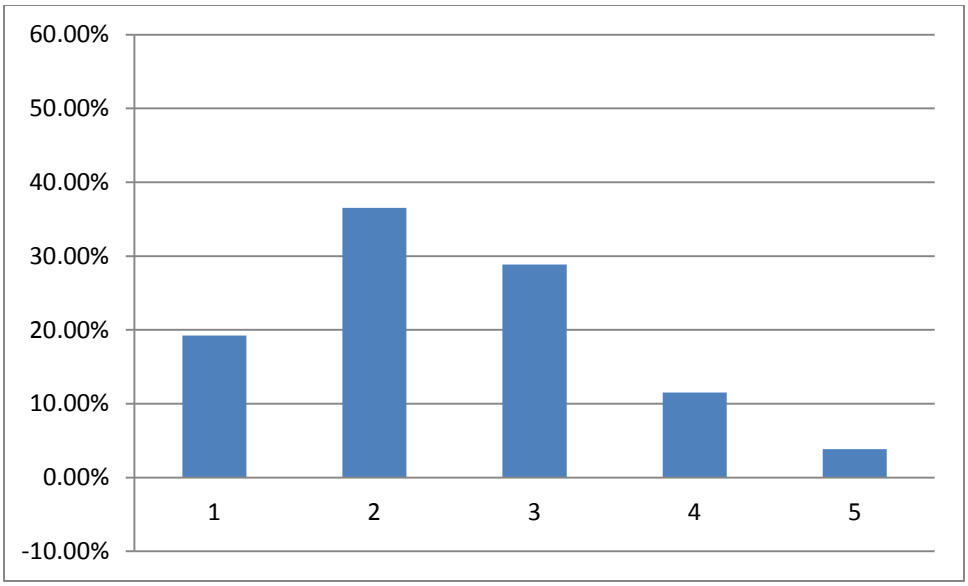

Figure 2) Self-Assessed Mechanical Design Skills before the Potato Cannon Project

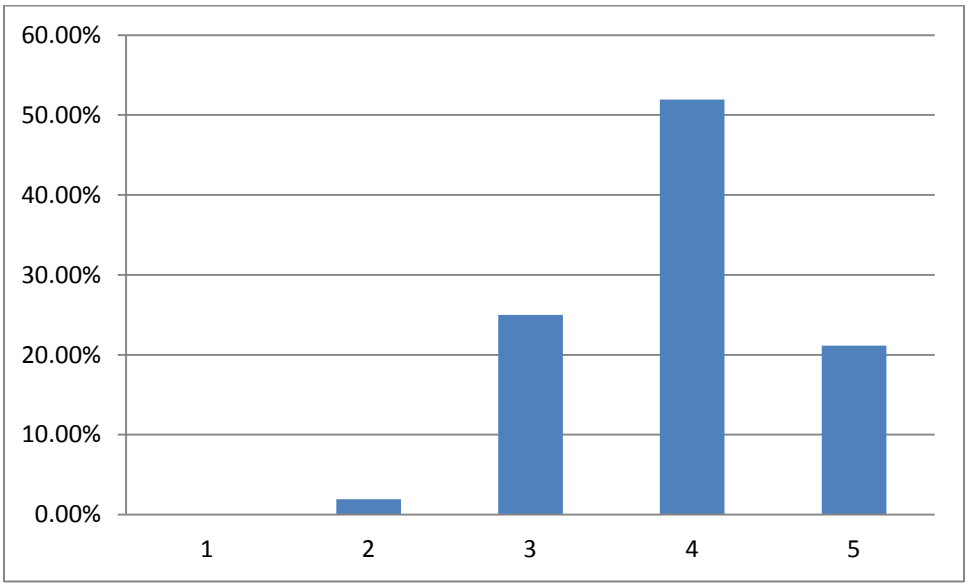

Figure 3) Self-Assessed Mechanical Design Skills after the Potato Cannon Project

Self-Assessed Fabrication Skills

As shown in figure 4, at the time of the pre-assessment there was a roughly uniform distribution of student beliefs concerning their ability to manufacture things, and their average fabrication score was 2.76. By the completion of the project, work in the machine shop in addition to various types of assembly work skewed the distribution of scores to the right, (see figure 5), resulting in an average self-assessed fabrication score of 3.9.

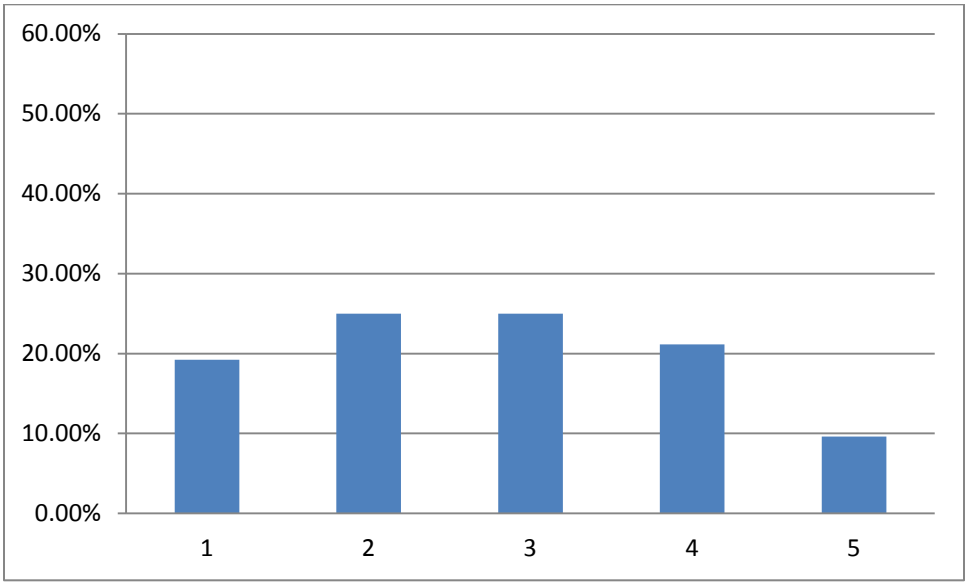

Figure 4) Self-Assessed Fabrication Skills before the Potato Cannon Project

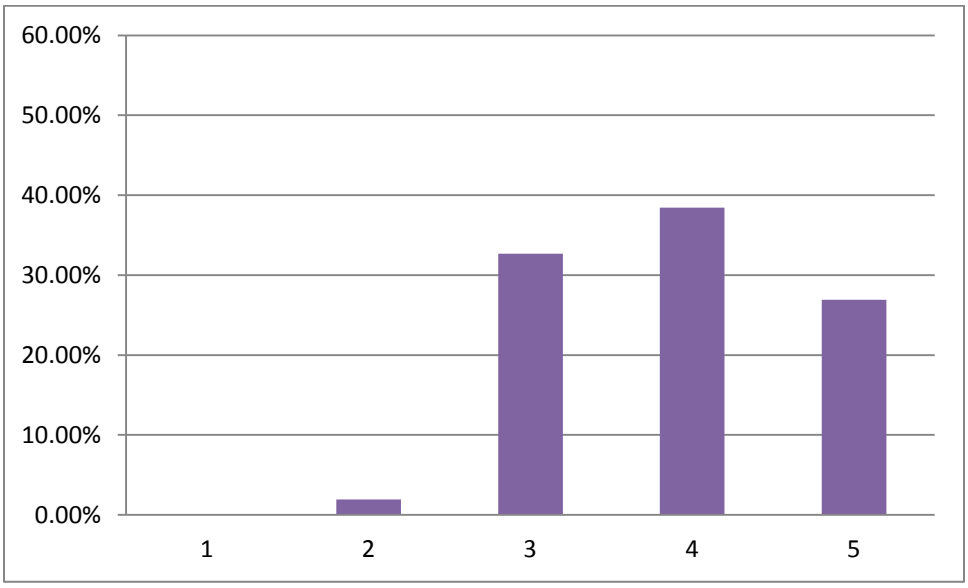

Figure 5) Self-Assessed Fabrication Skills after the Potato Cannon Project

Self Assessed Electronics Skills:

Prior to the Potato Cannon project, most students had very little exposure to electronics and as depicted in figure 6, the distribution of self assessed electronics skills was skewed to the left; an indication of low confidence. During the project, students were exposed to a variety of circuits, wiring diagrams and debugging. As a result, student confidence in their electronic skills grew as

indicated by the increase in their self assessed electronics skills from 2.02 to 3.08, with over 75% of the class reporting scores 3 or greater, (see figure 7).

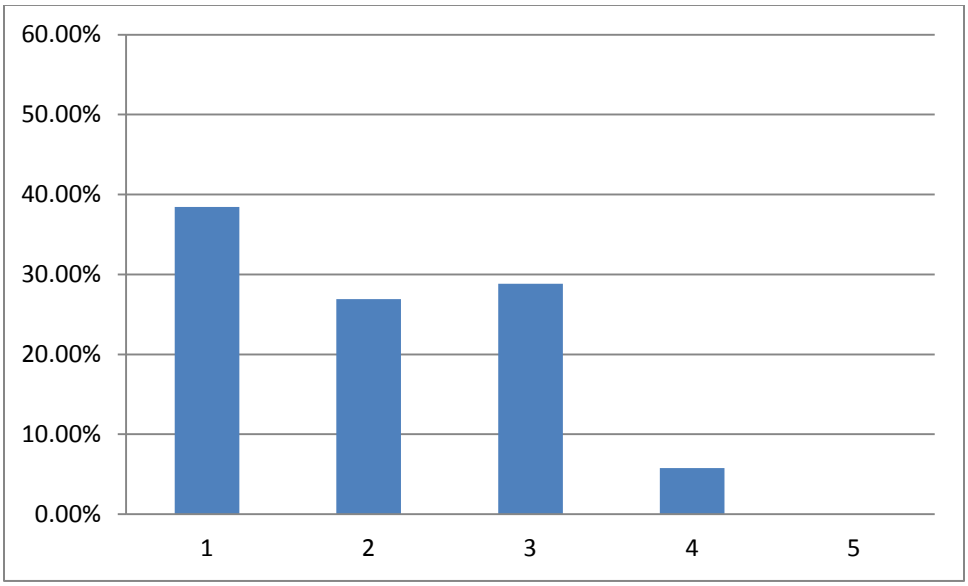

Figure 6) Self Assessed Electronics Skills before the Potato Cannon Project

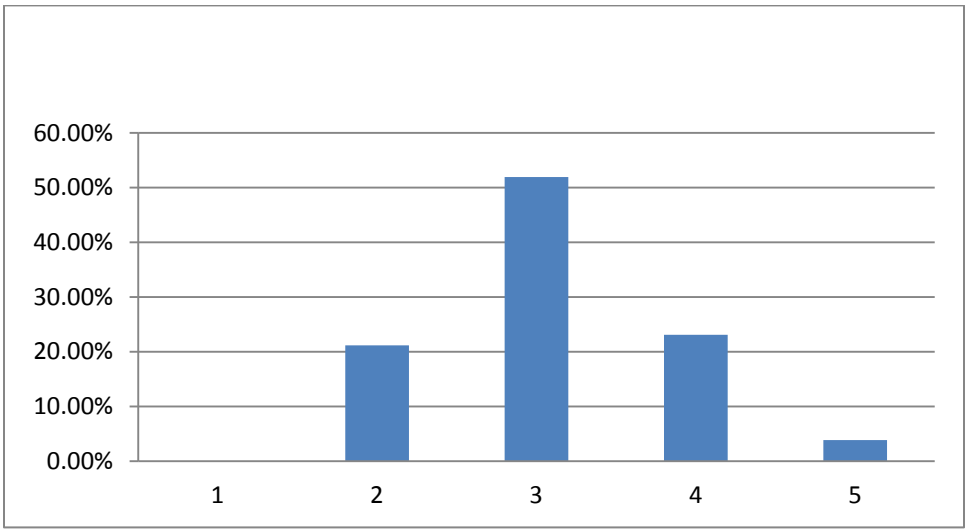

Figure 7) Self Assessed Electronics Skills after the Potato Cannon Project

It should be emphasized that only 27% of the class claimed to be highly confident about their electronics skills, (self assessed electronics scores of 4 or 5), as compared to 73% and 65% of students that were highly confident in their mechanical design and fabrication skills respectively. In the future, more background material about the circuits and devices the students used for this

project could be included to increase students understanding of electronics by encouraging their exploration outside of class.

Self-Assessed Programming Skills

Programming skills were by far the weakest area for students in the ME-105 course, and the skill for which they showed the least confidence, (see figure 8). The average programming skills score prior to the project was only 1.90, with less than 10% of students indicating any significant confidence in their ability to program. Through the use of the Arduino microcontrollers, students were exposed to fundamental programming concepts, but in point of fact were only asked to modify existing programs, not write their own from scratch. It had been intended to let students write more significant programs during the integration phase of the project, but insufficient time allotted for mechanical assembly and the final electrical integration forced instructors to reduce the programming task. As shown in figure 9, the final distribution of programming scores does move to the right, with an overall average of 2.92 for a change of 1.02 Likert points. While the lab appears to have had a positive impact on students confidence about their programming skills, only 25% of students surveyed report significant confidence in their programming skills, (i.e. a programming score of 4 or 5), suggesting that more needs to be done in this area. Possibilities for the future include adding more time to the project by eliminating other sections of the course, or simplifying the project to allow for more time on each task.

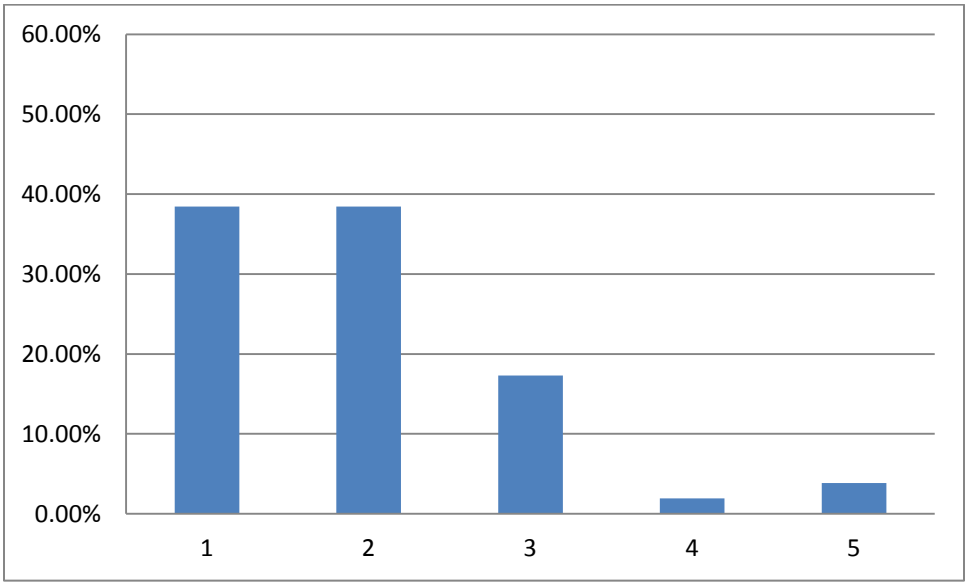

Figure 8) Self Assessed Programming Skills before the Potato Cannon Project

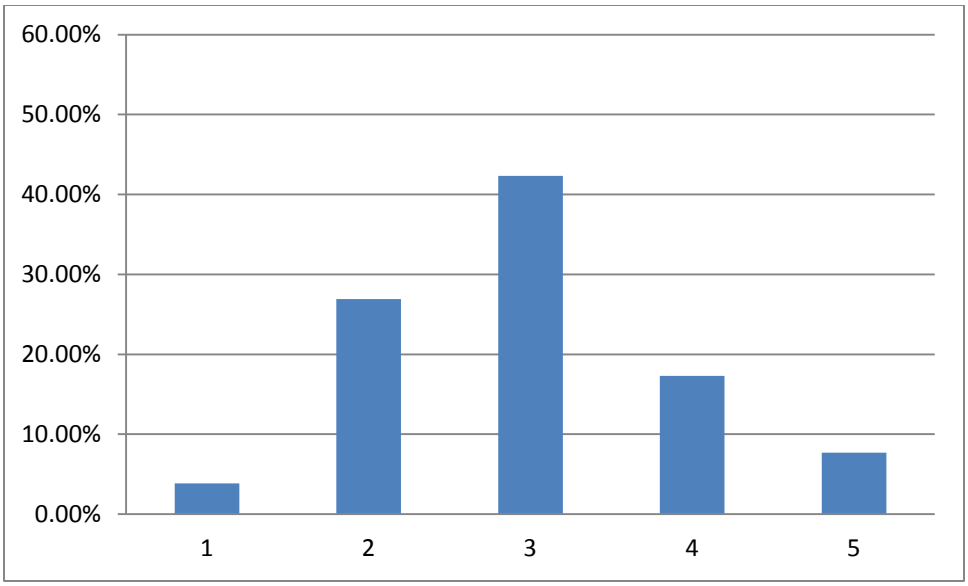

Figure 9) Self Assessed Programming Skills after the Potato Cannon Project

Self-Assessed Interest in Electro-mechanical Design Projects

The final question on the post-project assessment was for students to rate their interest in taking part in electromechanical design projects in the future. Admittedly, the goal of this first exposure to electro mechanical design was not to achieve mastery, but to stimulate interest

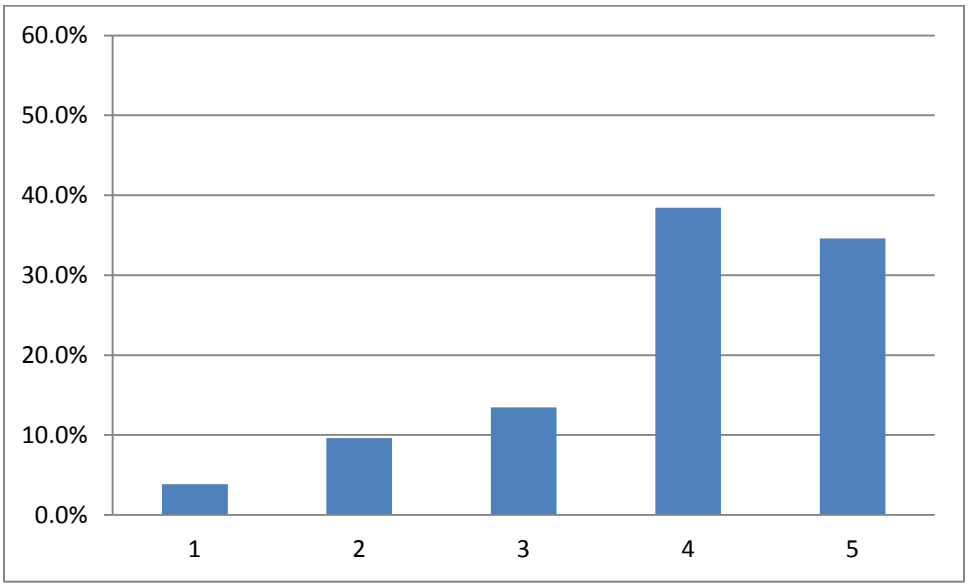

Figure 10) Students Interested in Working on Electromechanical Design Projects in the Future

And prime students with the confidence they need to excel in subsequent course work on mechanical design, electronics and programming. Figure 10 shows that 73% of students in the class responded to this survey question with a 4 or a 5 indicating that they were positive about the possibility of working on more electro-mechanical design projects in the future.

Conclusions

Pre and Post project assessments showed that in all of the four areas considered, (mechanical design skills, fabrication skills, electronics skills and programming skills), self-assessed skill levels increased an average of 1.17 points on the Likert scale, over the duration of the potato cannon project. These results indicate that students who participated in the project experienced positive changes in their confidence levels for each component area of electromechanical design. Over all, students were least confident in their non-mechanical skills with only a quarter of the class rating themselves strongly in the areas of electronics and programming. Part of this phenomenon may stem from having tried to do too much with the potato cannon project in too little time. Providing more lab sessions for the project to allow students the time for deeper investigation of electronics and programming could boost their understanding and confidence in these areas. Alternatively, simplifying the project in some way could free up time within the existing number of lab sessions; possibly eliminating the stepper motor powered aiming mechanism and giving students more flexibility with the programming and design of the potato cannons pneumatic subsystem. Despite the fact that certain aspects of the potato cannon project need to be revisited and fine tuned, the vast majority of students involved with the project expressed strong interest in working on electromechanical design projects in the future. This is the true measure of success of the potato cannon project, as students who are excited and motivated are more likely to stay in engineering than those who are not. Future work will involve tracking the current cohort of students as they progress through the mechanical engineering program to see if their experience in the Arduino Controlled Potato Cannon project had long term effects on retention.

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