AC 2010-476: IMPLEMENTATION OF A COMPLEX MULTIDISCIPLINARY CAPSTONE PROJECT FOR STIMULATING UNDERGRADUATE STUDENT DEVELOPMENT

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Implementation of a Complex Multidisciplinary Capstone Project for Stimulating Undergraduate Student Development

Abstract

Complex, multidisciplinary capstone projects require multi-faceted teams of faculty and students, representing two or more technical areas of expertise. Engineering education has emphasized more multidisciplinary work as graduates are expected to perform on multidisciplinary engineering teams and have some working knowledge in other engineering disciplines. The need for multidisciplinary educators to work together as a team requires coherent effort with excellent communications between faculty members from different departments. Many of the challenges from these complex projects can be minimized by the faculty, allowing the students to expand their engineering education experiences. The scope and depth of these complex projects must be tailored to the student team and requires periodic checks to ensure customer requirements and course objectives are met. This paper highlights a complex, multidisciplinary capstone project with students and advisors from different departments: electrical engineering, mechanical engineering, physical education, and behavioral science. This organizational structure is important, allowing the multidisciplinary faculty team to synchronize their efforts, bringing their individual strengths and resources together for developing an advanced prosthetic to promote student learning. This paper illustrates some of the project details employed between four separate departments to advance and enrich a multidisciplinary capstone project. Advantages to empowering a multidisciplinary faculty are also described. The techniques described allow the students to benefit from the work of a diverse, multidisciplinary faculty team and enrich the students' understanding by bringing in real world projects.

Introduction

Government as well as private industry and many academic institutions feel that it is important to integrate engineering because many modern systems are developed with integrated engineering teams. In 2005 the National Academy of Engineering in "Educating the Engineer of 2020," stated many benefits and merits of co-teaching, just in time teaching, and multi-disciplinary teaching.[1] Recent program outcomes criteria published by ABET have included in its list of a-k criteria, a requirement for engineering programs to demonstrate that students have "an ability to function on multidisciplinary teams."[2] Even discipline specific organizations have identified the need for their disciplines to cross boundaries. In the "2028 Vision for Mechanical Engineering,' ASME directs attention to the complexity of advanced technologies and the multiple scales at which systems interact. Both will require engineers to team up in developing multidisciplinary solutions.[3] In "Vision 2020: Reaction Engineering Roadmap," from AIChE, participants acknowledged the need for multidisciplinary education to handle highly integrated knowledge and suggested incentives and resources for development of interdisciplinary courses.[4] Drexel University (Philadelphia, PA) developed the program "Enhanced Experience for Engineering Education (E4)."[5] This program joined students and faculty from all engineering disciplines for the first two years of the student's engineering education and provided an intense integration experience. However, many academic institutions integrate students much later through coursework and capstone projects. One advantage of a later integrative experience is that the students are much more developed in their engineering discipline, and new knowledge is built on an established base.

The engineering program at the United States Military Academy (West Point) is designed to promote academic development in a wide variety of traditional subjects essential to future professional service. Capstone projects are one way to exercise and capitalize on this collective engineering knowledge. Additionally, capstone projects can draw complementary disciplines closer together. It is not difficult to find a mechanical system that has an electrical component or requires some computer coding and vice versa. Requiring the students to see a broader picture across several disciplines also requires the instructors to change their single discipline practices.

Inherent in a capstone advised by multiple instructors is the obvious advantage of the shared responsibility and workload. The individual advisers can use their initiative and department resources to develop or refine materials for the capstone team. It is essential that the strengths and weaknesses of the individual advisers are assessed in order to share duties. Each adviser can help students develop solutions, so the students see the same design process, engineering, and mathematics applied to different fields. A single discipline adviser team would miss opportunities to appeal to students of different disciplines working on the same project. The instructor team operates more effectively with open collaboration. Since students come from several academic majors, the diversity is advantageous to all concerned and keeps the advisers from the different departments engaged in the projects.

It is well documented in general literature on multidisciplinary teaching that the greatest difficulty for the instructors is the time and energy required to work as a team.[6-8] In this capstone project with requirements and application to computer science, and mechanical and electrical engineering, the advisers agree that careful time management and planning are vital. Scheduling meetings between faculties of the different departments as well as work time for the students is more difficult, but a committed advising team can make it work.

Although the capstone experience may be advised by a single advisor, advisors from multiple departments are encouraged. This paper focuses on and examines the multidisciplinary capstones, required at West Point of all mechanical and electrical engineers. Although several multidisciplinary capstones exist at the school and have similar results, the authors will specifically compare the results of a powered prosthetic foot to the overall capstone experience. The capstone is conducted with students and faculty advisers from four departments: electrical engineering, mechanical engineering, physical education, and behavioral science. Project advisors are from four different departments and use a team-teaching approach to develop, mentor, and improve the multidisciplinary capstone. Traditional capstones usually involve discipline specific instructors focused on their area of technical expertise to guide the students. This capstone required an aggressive start by the advisers to develop and mature the project for undergraduate students to contribute as a multidisciplinary team. Additionally, various outcomes from the capstone experience and insights gained from the project advisors are presented. This particular capstone has recently been developed, and this is the first time to assess the effectiveness of such an aggressive start by the advisors in the department.

Background

The capstone course devotes 3.5 credit hours to engineering design. This course provides experience in the integration of math, science, and engineering principles into a comprehensive engineering design project. Open-ended, client-based design problems emphasize a multidisciplinary approach to total system design providing multiple paths to a number of feasible and acceptable solutions which meet the stated performance requirements. Design teams are required to develop product specifications, generate alternatives, make practical engineering approximations, perform appropriate analysis to support the technical feasibility of the design, and make decisions leading to an optimal system design. System integration, human factors engineering, computer-aided design, maintainability, and fabrication techniques are addressed. This course provides an integrative experience in support of the overarching academic program goal, and is often interdisciplinary in nature. Students spend extensive time in project development laboratories fabricating and refining their final products.

The course learning objectives are:

- Apply the Engineering Design Process to design and build creative solutions for open-ended engineering problems.
- Work effectively within a multidisciplinary design team in a professional and ethical manner.
- Develop and conduct experiments/tests, and analyze and interpret results in support of the design process.
- Apply knowledge of mathematics, science, and engineering in support of the design process.
- Communicate effectively in the design process, in technical reports, and in design presentations.

The West Point Bionic Foot is one of the most successful examples of these types of projects. A newer faculty member aggressively sought resources and members for a faculty team upon arrival. Collectively, they structured a complex, multidisciplinary project tailored to undergraduate student capabilities.

The Bionic Foot Project

A team of faculty, staff, and undergraduate students from Mechanical Engineering, Electrical Engineering, Computer Science, Engineering Psychology, and Kinesiology together with clinicians from the Keller Army Hospital and Walter Reed Medical Center in collaboration with private industry partner SpringActive, Inc., seeks to tackle several leading technical challenges that prevent the development of a truly biomimetic, foot-ankle, prosthetic device. One of the primary challenges is prohibitively low power and energy density in traditional actuation schemes. The ankle joint requires considerable power and energy and applying a traditional approach with a DC motor and gearbox at the ankle joint would force the system to become too heavy and bulky.

A portable, daily-use powered prosthesis requires both high power to weight ratio (power density) and energy to weight ratio (energy density) in an actuator. Without these limitations, one could take, for example, a RE75 DC Motor from Maxon Precision Motors, Inc. rated for 250W continuous power to provide the 250W peak power required in human gait (80 kg subject at 0.8 Hz walking).[8] However, this motor in combination with a gearbox in a traditional approach would weigh 6-7 kg, which exceeds the weight of a typical, biological, below-knee limb. In addition, the size of the batteries needed to power the system would become too large and heavy making the system unmanageable. This issue of low power and energy densities is a main reason that keeps the current state of the art, portable, transtibial devices from providing 100% of the power and ankle motion required in all ranges of walking and running gait.

Today's foot-ankle prosthetic devices are still largely passive. They typically use rubber like springs or leaf springs made from carbon composite materials such as the commercially available Ossur Cheetah Foot, which is specifically tailored for running. Arizona State University's SPARKy device, featured in the January 2010 issue of National Geographic Magazine, which was developed by members of this project, can provide up to 400 Watts of peak power.[9] MIT, Vanderbilt, Michigan and several other academic and private researchers have developed powered walking devices. However, no fully powered, computer controlled walk-run device exists today. A walk-run device is highly desirable especially for the active military amputee. Amputees consume 20 to 30% more energy with their passive devices. Asymmetry in gait caused by the lack of ankle joint motion and active ankle power result in long-term health risks such as arthritis.

The purpose of this project is to design, build, and test a motorized foot-ankle prosthetic device that utilizes biomechanical energy regeneration to reduce the electric motor and battery to self-portable weight and volume. Energy regeneration is typically thought of as the capture and conversion of negative mechanical energy to electric energy as is done in electric cars with regenerative braking. In this project, biomechanical energy regeneration is the storage of negative mechanical energy in springs to be used as mechanical energy without the need to undergo the inefficient energy conversion process from mechanical to electrical back to mechanical.

A Robotic Tendon[8] actuator, Fig. 1, is utilized in this device to minimize the peak motor power requirement by correctly positioning a uniquely tuned helical spring so that the spring provides most of the peak power required for gait. The Robotic Tendon is a small and lightweight actuator that features a low power motor that is used to adjust the position of the helical spring using a very robust position controller. Fig. 1 illustrates how the desired spring deflection and consequently via Hooke's Law the desired force and ankle moment is achieved using a spring in series with a motor. As the ankle rotates over the foot during the stance phase, as illustrated in Fig. 1 by the inverted pendulum model, the spring is extended by the falling center of mass of the body. Additional deflection in the spring is achieved by correctly positioning the motor so that the desired ankle joint angle and moment is realized. A heavy, powerful motor is not needed because the Robotic Tendon, similar to the biological tendon-muscle complex, stores a portion of the stance phase kinetic energy and additional motor energy within the spring. The spring releases its stored energy to provide most of the peak power required during "push off." Therefore, the power requirement on the motor is significantly reduced. As described in [8], peak motor power required is 77W compared to 250W for a direct drive system in the 80 kg subject at a 0.8 Hz example. Consequently, the weight of the Robotic Tendon, at just 0.95 kg, achieves a power density that in essence is 7 times greater than a traditional approach.

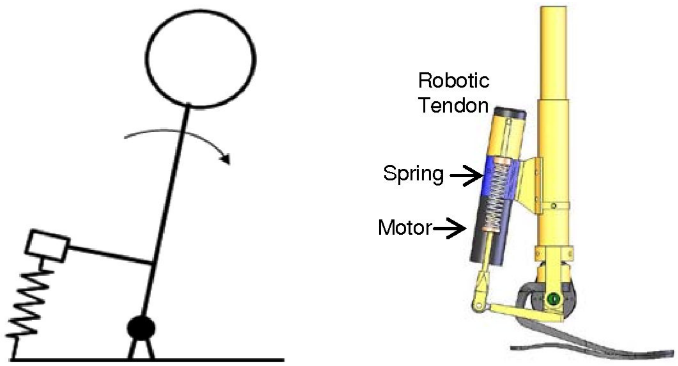

Fig. 1: Desired spring deflection is achieved by controlling the motor position and capitalizing on the cyclical nature of gait. As the tibia rotates over the stance foot, springs are extended. Simultaneously, the motor extends the springs to achieve the desired spring deflection and the forces required to generate the required ankle moment for walking. This inverted pendulum with a lumped mass illustrates the regeneration energy with use of a spring in series with a motor. Computer aided design model of the prototype is illustrated on the right.

The bionic foot, Fig. 2, is controlled in real time using Real Time Workshop and Simulink from Mathworks.[10] The Simulink model is compiled on to the embedded target PC running the xPC Target Operating System. An encoder at the motor, an encoder at the ankle joint and an optical switch embedded at the heel provides the necessary sensor feedback. Advantech's 650MHZ PC-104 with 512MB on board memory is selected to run the system. A multifunctional I/O board from Sensoray Co., Model 526, which is connected to the PC104 via an ISA bus, controls a RE-40 Maxon DC motor with encoder feedback. Future prototypes will make use of a computing system fully contained in the prosthesis.

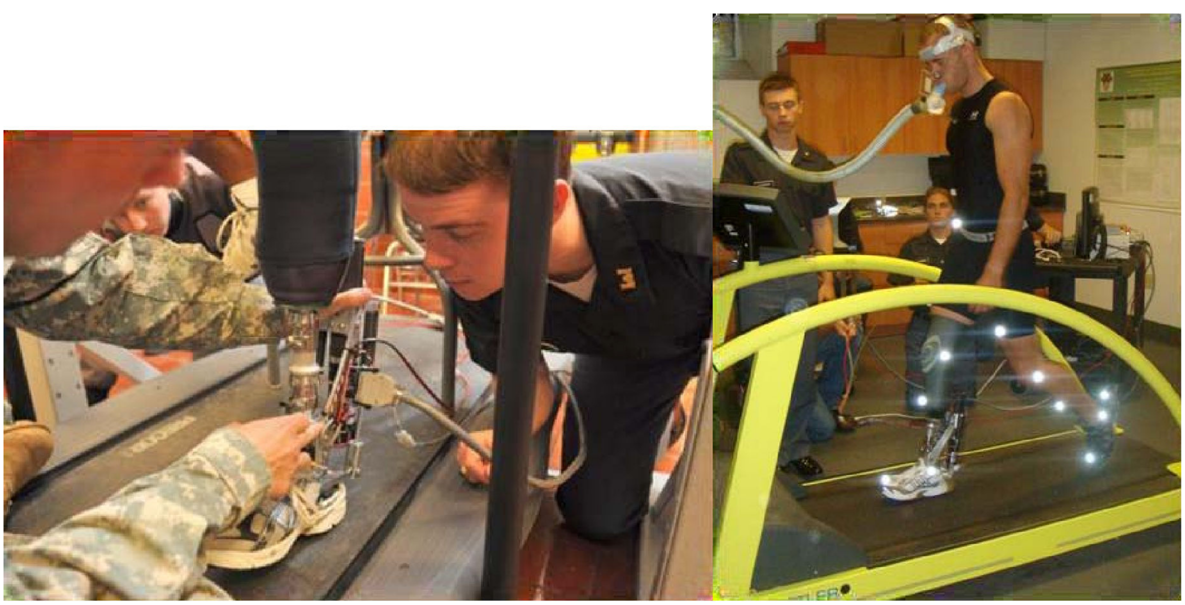

Figure 2: Bionic Foot in operation with fitting and adjustments on the left and biomechanical monitoring conducted during testing on the right.

Project Structure

Due to the complexity of the project, a diverse group of faculty from various departments team to provide the necessary technical guidance. The lead advisor from Mechanical Engineering provides overall project leadership and mentor students from Mechanical Engineering. Faculty advisors from Electrical Engineering and Computer Science, Kineseology, and Engineering Psychology provide specific expertise and mentor sub-teams composed of students from their departments. In addition clinicians and other external experts provide project support from patient recruitment, clinical support, and professional engineering support. The students elect their project leaders from this group of students assembled from the various departments. This year the team leader is a Mechanical Engineering student, the assistant team leader is from Electrical Engineering. Functional areas such as power, electronics, software, mechanical design, and testing are assigned to the students. All of the students receive credit for this project as their culminating year-long two course design sequence.

To support the integration of this diverse team of students who are from different disciplines and physical location within the campus, the institution aligned the course scheduling of the one-year mechanical, electrical, and computer science programs' design sequence. This allows the students to meet every other day during class hours for the project. The Kinesiology and Engineering Psychology programs' design sequence are not aligned with the other three programs. This does add challenges to the team because these students may not be available during scheduled project hours. The Mechanical Engineering program, as the lead organization, has created the project space within the department for the team. The advisors, leveraging external research funding obtained for this project, took care to equip the space with the required design, fabrication and test equipment that the students regularly used in their discipline specific courses. This established a familiar and coherent physical environment for the team. Another highly effective integrative technique used by the team is the SharePoint collaborative environment. All of the project products for this project are stored in this environment. Of particular help seems to be the products of the previous year's team which is accessible in the collaborative environment.

Cutting Edge Research with Undergraduate Students

Undergraduate students are capable of supporting highly complex cutting edge research. The key is to scope their portion so that they can be successful given their level of expertise and available time. For example, in the mechanical design effort, characterization of the kinematics and kinetics of gait is prepared by the faculty advisor and given to the students as a set of engineering requirements. Given these parameters, students conduct the computer aided design using Solid Works and validate the design using finite element analysis using COSMOS. The advisors provide the students fabrication and machining advice and assist their fabrication effort. Similar process is used with software, electronics, control, and testing efforts.

Expected Outcomes and Assessment

One of advisors' goals was to assess the effectiveness of the multidisciplinary capstone experience and compare it to single disciplinary teams. A look at the course feedback data from recent students taking the capstone course shows some interesting and encouraging results (Figures 3-6). For the most part, the students agree that the multidisciplinary capstone is a positive experience for them and is better than other single discipline capstones. Since a few capstones are multidisciplinary, the results are compared to the overall capstone results which include both single discipline and multidiscipline teams. Particular ratings that are addressed in the discussion are indicated on the graphs. There were three multi-disciplinary capstone teams with a total of nine survey responses across the three teams. These responses are compared to 48 responses from all of the students participating in an ME capstone project, 587 survey responses from students in the ME program across all ME courses taken that semester, and over 20,000 responses from students across the institution in all of their courses that term. The following scale based upon a Likert scale from 1 to 5 (Table 1) was used for the students' survey:

Table 1: Assessment Scale

1	2	3	4	5
strongly disagree	disagree	neutral	agree	strongly agree

The following assessments address the objective ratings above. Student comments and discussion on the student surveys reinforce their overall ratings. Additionally, the rating scale is a standard set of responses used at West Point for student surveys. Students and faculty alike are familiar with this set of responses and their interpretation.

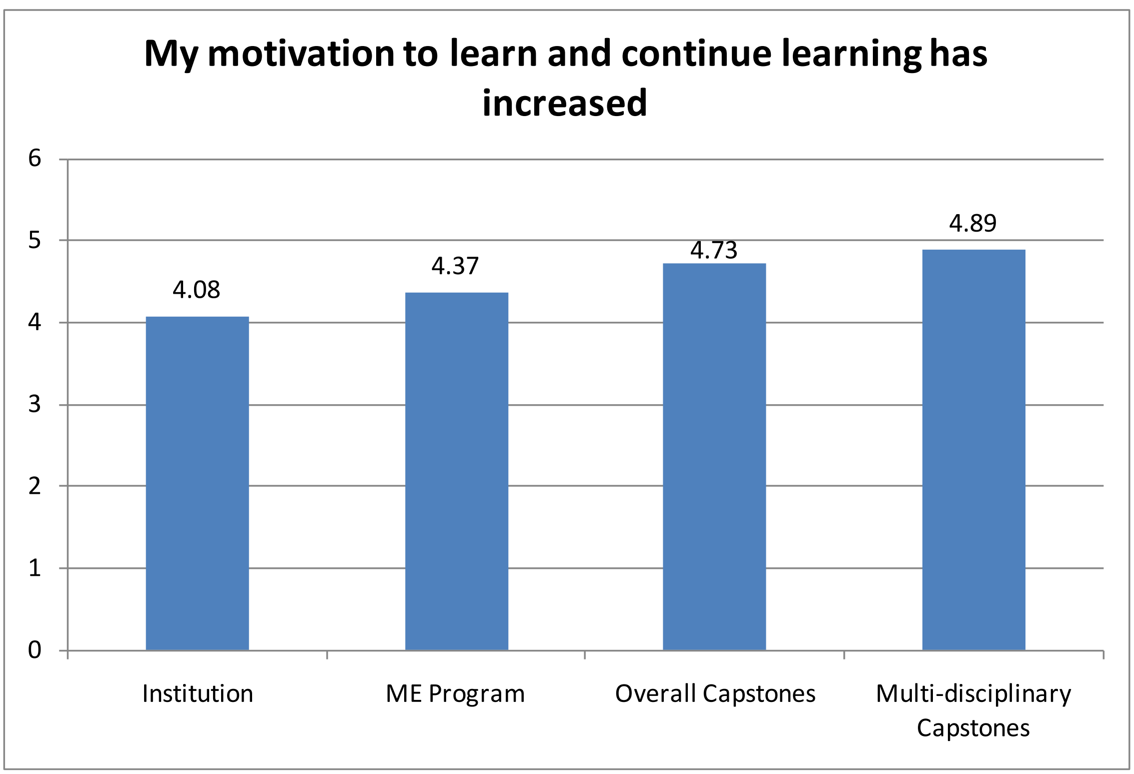

Figure 3: Student Motivation

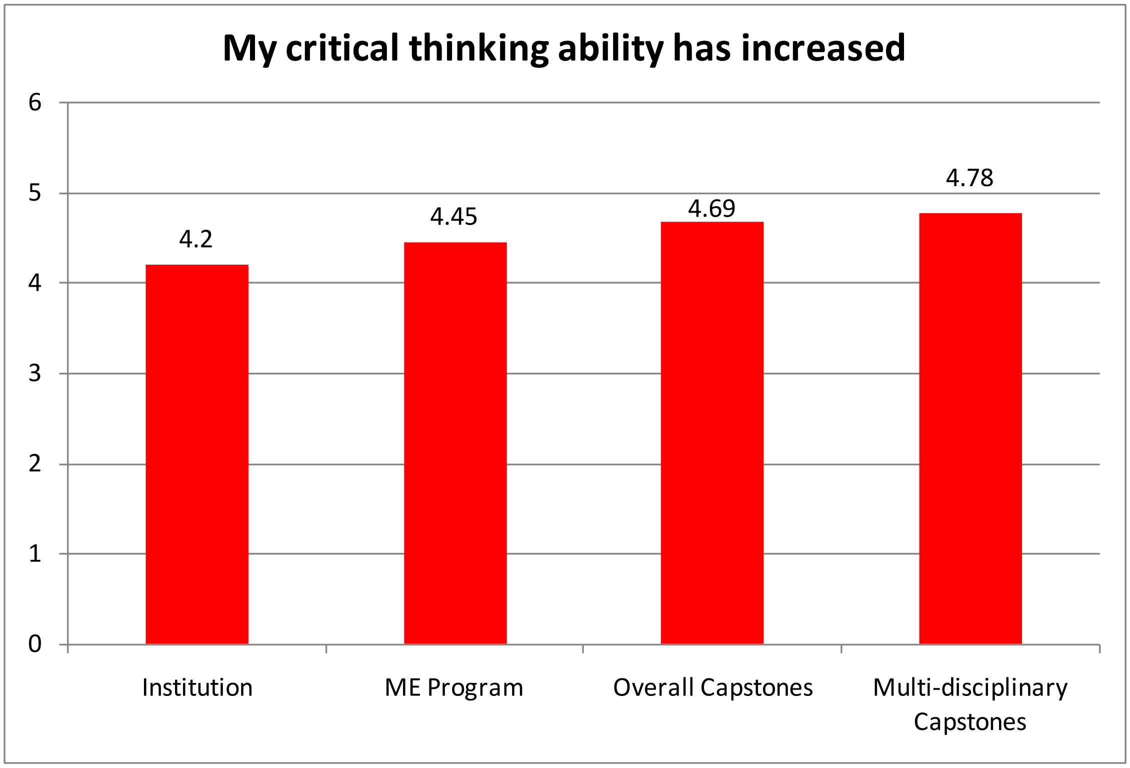

Figure 4: Critical Thinking

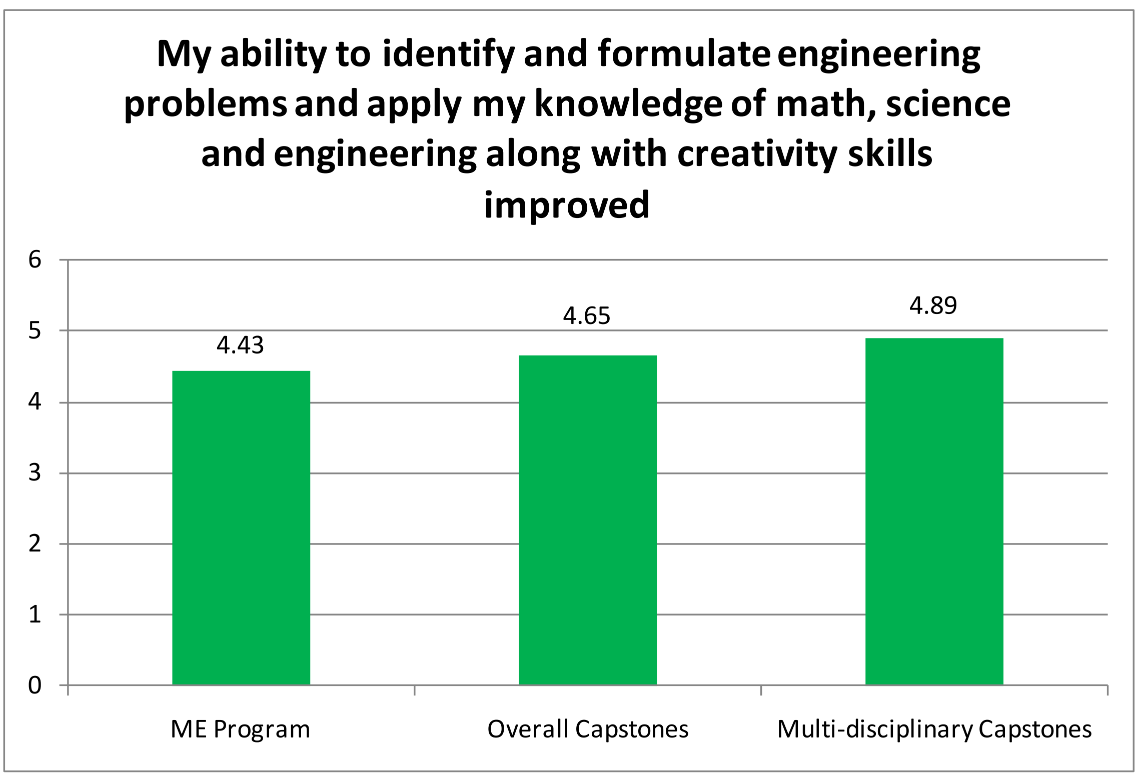

Figure 5: Creativity Skills

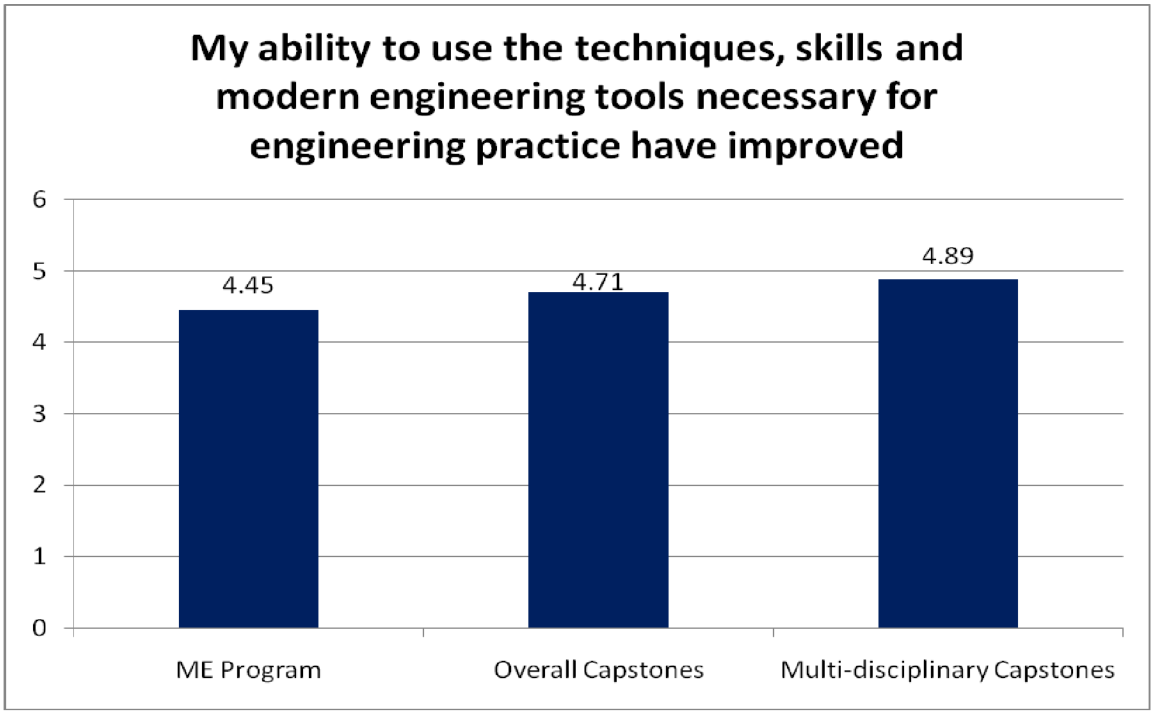

Figure 6: Overall Ability

A positive trend can be seen in Figures 3-6, and averages were higher than institutional norms for single discipline capstones. Students indicated more satisfaction with the multidisciplinary capstones which resulted in higher averages. The collaborative environment among the faculty team lends to better advising and techniques than advising with a single discipline's limited insight to the broad material application. Likewise, students felt more motivated to learn since the material was applicable in several areas. The engineering students could see the relationships among different fields. One student commented, "The instructor had a great wealth of knowledge about the material covered. He was always willing to spend extra time to make sure that everybody understood the information." One of the most significant developments was that the students felt an increase in their critical thinking aptitude. Gaining self-assurance in their ability to work with or understand another discipline in some depth, the students were more comfortable with the challenge.

We feel the multi-department faculty advisor model and structure are advantages and are in the process of further assessing this organization.

Contributions and Future Work

In addition to the observations of advising a multidisciplinary capstone, regarding the advantages and limitations, this initiative provides guidelines to develop and implement other multidisciplinary capstones for undergraduate students. Multidisciplinary engineering capstones could stimulate faculty and students to approach other departments to conduct multidisciplinary research and conduct other joint and collaborative design projects. Multidisciplinary projects are also highly encouraged from the departments but also help the student become more knowledgeable and valuable in their future positions. Future work includes integrating other departments and organizations as this project matures.

Our short term goals were to evaluate the multidisciplinary capstones that could make an immediate impact to the students' learning. We intend to use the results and information to stimulate additional interest in other departments, faculty, and students to further participate and initiate multidisciplinary capstone projects. This will better prepare our future engineers to face the multidisciplinary systems and problems that exist today.[1-4]

Conclusion

The advantages, challenges, and assessment of a multidisciplinary capstone experience extend beyond course content of electrical, mechanical, and computer science programs. The benefits of sharing applied engineering and math, dealing with various systems, learning through generalization of problems and applying knowledge to different disciplines provide enthusiasm among students and faculty. These benefits, gained from committed faculty members working as a team, support program goals sought by the different disciplines as well as the vision of a multidisciplinary capstone project. The multidisciplinary capstone model described in this paper can foster partnerships between various engineering departments and disciplines. Nevertheless, advising a multidisciplinary capstone requires a committed, motivated faculty who are creative and willing to change. Cultivating multidisciplinary capstones such as the Bionic Foot is a developmental experience for the faculty as well as the students, but the rewards are worth the additional time required to make it interesting and relevant to the students.

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