2006-617: ADVANCED MECHATRONICS: DEVELOPMENT OF A COURSE ON SENSORS & ACTUATORS FOR MECHATRONIC SYSTEMS

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Advanced Mechatronics: Development of a Course on Sensors & Actuators for Mechatronic Systems

Abstract

Mechatronics refers to the growing number of commercial products and industrial processes that involve the integrated application of mechanical and electrical engineering concepts. Despite the importance of this interdisciplinary area, many of today's engineering graduates are unprepared to function competently in environments that require them to optimally integrate electrical and mechanical knowledge areas. In addition, engineers with better communication and teamwork skills are needed to ensure U.S. competitiveness in today's global economy.

In order to address this competency gap a team of faculty members (consisting of faculty from both ME and EE departments) started work in the late nineties to integrate Mechatronics-based activities at all levels of the undergraduate engineering curriculum at University of Detroit Mercy. These included a new senior level technical elective in introductory mechatronics along with mechatronic activities in freshman design and in the introductory electrical engineering course for non-EE majors. This effort has been very successful, and now mechatronics activities take place in many pre-college programs that the school runs.

Just over two years ago this team received a National Science Foundation grant to build on the earlier efforts by developing two new advanced courses in the area of Modeling & Simulation of Mechatronic Systems and in the area of Sensors & Actuators for Mechatronic Systems. The first of the two courses has been taught in Winter 2005 and reported on, while the second course was taught in Fall 2005. This paper will describe in detail the construction of the Sensors & Actuators course, as well as results of outcomes assessment conducted by an assessment expert who is also part of our team.

1. Introduction

Mechatronics is defined as the synergistic combination of precision mechanical engineering, electronic control, and intelligent software in a systems framework, used in the design of products and manufacturing processes. Design of modern day products involves the knowledge of different engineering disciplines, as well as an ability to communicate and work well in multi-disciplinary teams. Because engineers are traditionally trained in fields such as either Mechanical or Electrical engineering, many of today's engineering graduates are not well prepared to function competently in environments that require them to work on products where electrical and mechanical knowledge areas are intertwined.

An ongoing NSF-funded project addresses these competency gaps through the development of two courses incorporating team-oriented and project-based activities, as a follow-up to previous efforts centered around the development of an "Introduction to Mechatronics" course[1-5]. For this project, we have identified the following goals: (a) to address the need of industrial partners to have engineers educated in the principles and applications of mechatronics, (b) to improve student competencies in communication skills, teamwork, and project management through the increased use of team-oriented, project-based, interdisciplinary approaches to instruction in mechatronics, (c) to increase in engineering students an appreciation for lifelong learning by delivering instruction in mechatronics to this population, and (d) to increase the participation of women and underrepresented minorities in engineering by engaging the freshmen and pre-college populations in hands-on instruction in sensors and actuators.

To achieve these goals, a number of activities have been completed. Two new courses in mechatronic system modeling and simulation, and sensors and actuators have been developed and delivered as technical electives for upper-division engineering students of both the Mechanical and Electrical & Computer Engineering Departments. The first course has been reported on in ASEE 2005[6]. The first offering of the second course has just been completed and is addressed in this paper. A 90-minute hands-on module on Sensors has been developed and used in two different pre-college settings. Materials developed for the sensors and actuators course will be adapted for use in additional hands-on pre-college learning modules. An important feature is a plan for assessing the outcomes of the project; the project team includes a professional evaluator who has worked closely with the engineering co-PIs of the grant, who are from two different engineering disciplines.

2. Addressing the Project Goals

The University of Detroit Mercy (UDM) is uniquely situated to play a major role in mechatronics instruction in the local region. The predominance of the auto industry in the Detroit area, the mandatory cooperative education program, the diversity of our student population, and our ongoing relationships with enthusiastic industry partners are but a few of the factors that position UDM to be a leader in this interdisciplinary area.

(a) The need of industrial partners to have engineers educated in the principles and applications of mechatronics has been addressed by the development and delivery of two new courses that build on an “Introduction to Mechatronics” course that was funded by an earlier NSF CCLI program grant in 1999. Sensors and actuators are key components in a mechatronic system, and so one of the new courses is dedicated to the study of these components, including devices that are based on new and emerging technologies such as micro electromechanical systems (MEMS). A finding from the “Introduction to Mechatronics” course suggested that skills in the modeling and simulation of mechatronics systems needed to be enhanced in the students served by the course. In the Detroit area, the auto industry and its ancillaries represent the single largest employer base. In recent years, the inclusion of electronics in many vehicle functions has created the demand for engineers who can design systems with integrated mechanical and electrical components. The modern automobile contains a large number of sensors and actuators that are integrated in mechatronic systems found throughout the vehicle. In addition, many producers are showing great interest in virtual prototyping, which requires the ability to derive an accurate mathematical model of a system, and to create simulations that accurately predict system performance.

(b) Improving student competencies in communication skills, teamwork, and project management has become a critical issue in the preparation of the nation’s technical workforce particularly in the context of the emerging model of the global workforce. Through team-oriented, project-based, interdisciplinary approaches to instruction in mechatronics, we continue to focus on these skills.

(c) Students taking the new courses will be able to better appreciate the need for lifelong learning. The modeling and simulation course, for example, focuses on the process of modeling systems rather than on learning the models that already exist for systems. Since new sensors and actuators are being developed on a continuing basis, students will be instructed on how to adapt to the use of newly developed devices. The sensors and actuators course includes significant treatment of new technologies such as MEMS. It also features a capstone project that requires students to engage in self-directed learning about a transducer not discussed in class.

(d) Increasing the participation of women and underrepresented minorities in engineering by engaging the freshmen and pre-college populations in hands-on instruction in mechatronics is facilitated by the introduction of mechatronic-based hands-on projects at the freshman and pre-college levels. The authors have already had considerable success in developing and delivering mechatronics modules for use at these levels[7-9]. UDM has an active outreach program that primarily serves an urban constituency, and the courses taught as part of that program continue to benefit from spin-offs generated by the mechatronics course development efforts. UDM's engineering programs already serve a diverse student population through outreach programs which benefit from the spin-offs of these new course development efforts, with a large percentage of students coming from groups that have traditionally been underrepresented in engineering. Furthermore, UDM has a long-standing commitment to urban outreach, and in particular, to urban youth. We believe that the incorporation of industrially relevant and exciting hands-on projects will improve the recruitment and retention of these segments of the population.

3. Course Content

The "Sensors and Actuators for Mechatronic Systems" course has been offered as a technical elective for both mechanical and electrical engineering senior undergraduate students as well as to graduate students. There were two formal weekly meetings for an hour and fifteen minutes each for the 14-week duration of the course. Apart from the lectures extra time was scheduled as needed to foster synergistic laboratory activities involving working with actual sensors and actuators.

3.1 Learning Outcomes

The learning outcomes for this course are as follows. After completing the course the student should be able to:

a) Understand the underlying physical principles of the basic transduction mechanisms of different sensors and actuators.
b) Understand the evolution of emerging sensor and actuator technologies such as micro electromechanical systems (MEMS).
c) Understand the fundamental principles of data acquisition.
d) Demonstrate the ability to apply self-directed learning skills by researching a sensor or actuator not discussed in class.

e) Demonstrate proficiency in the use of appropriate software tools that permit data and command interaction with common sensors and actuators.
f) Work collaboratively across disciplines and cultures on team exercises involving sensors and actuators.
g) Demonstrate effective oral and written communication skills in the context of collaborative team exercises involving sensors and actuators.

3.2 Testing Philosophy

Students were tested in the course through the following four components: quizzes, homework assignments, a capstone project, and a requirement to pass the online LabVIEW certification test. We now provide more details on the above testing elements. There were six quizzes conducted during the term and they tested concept-level understanding of the theoretical treatment of sensors and actuators provided in the lectures. It was realized during the planning for the course that a conventional theoretical treatment and associated testing of material would not be as effective as incorporating extensive laboratory exercises involving working with actual sensors and actuators. In this context it was decided that students would be required as part of the course to learn LabVIEW software[10]. LabVIEW is a graphical programming language that enables the creation of virtual instruments (instruments defined and configured in software) and is widely used in industry. In conjunction with appropriate data acquisition hardware, LabVIEW can be used to acquire and process data from sensors as well as to command actuators, if necessary, based on the results of processing. A total of seven homework assignments were assigned during the term. Some of them involved simple numerical calculations on sensors and actuators. But others (and this was the part that was most effective in achieving the learning outcomes) required considerable time to be spent in the laboratory collecting and processing data involving sensors and actuators. In light of the extended hours required of students in laboratory activity, it was decided to forego traditional tests completely. To provide an incentive to learn LabVIEW the students in the class were required to *individually* pass the LabVIEW fundamentals exam[11] made available online by National Instruments. The exam is made up of 40 quiz type questions out of which students are required to get 32 correct in order to pass. Upon passing the exam an official certificate is provided by National Instruments at no cost, which a student can use to enhance his/her resume. This proved to be a good incentive for students.

3.3 LabVIEW Exercise Component of Homework Assignment

The content of the homework assignments involving laboratory work will now be discussed in detail:

Experiment A: Carry out analog-to-digital conversion of a sinusoidal waveform from a signal generator. Write a LabVIEW program to count the number of zero crossings of the waveform. Obtain and display the spectrum of the waveform. Repeat using a voice input captured through a microphone and associated amplifier. Extend the program to perform digital-to-analog conversion on the stored samples and display the output signal on an oscilloscope (for the sinusoid) or play it on a speaker (voice signal). This experiment served as an icebreaker for using LabVIEW; specifically it demonstrated the ability to acquire, process, and output data. In addition it helped to illustrate the Nyquist sampling theorem and the concept of the spectrum.

Experiment B: Construct a virtual instrument to control a stepper motor such that it executes a specified motion sequence.

Experiment C: Construct a virtual instrument to obtain the speed vs. applied voltage characteristics of a DC motor and to demonstrate simple closed-loop speed control. The given motor had a built-in optical encoder that enabled speed measurement. Its speed was controlled through a pulse width modulation arrangement involving an H-bridge. The DC motor setup is shown in Figure 1 below.

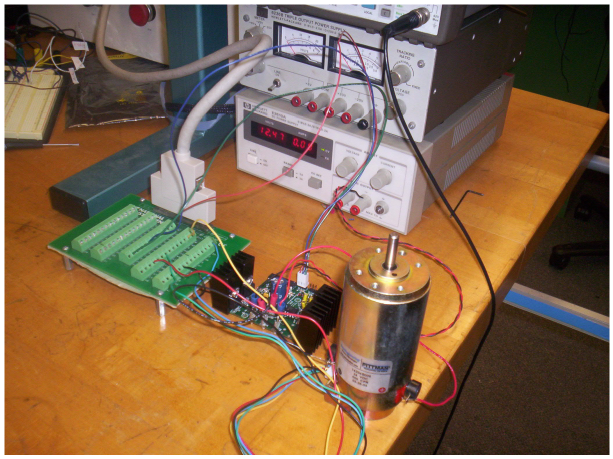


Figure 1: DC motor speed control

Experiment D: Use data acquired from a 3-axis accelerometer while pushing it around on a cart as well as traveling in an elevator to recreate the path traversed. This experiment made use of a modular 3-axis accelerometer sold by Freescale and was used to illustrate MEMS technology. It also served to highlight the effect of noise on the post-processing of data collected from sensors. The cart with the accelerometer setup is shown in Figure 2 below.

Figure 2: 3-axis accelerometer on a cart

3.4 Course Textbook

The textbook used for the course was a book by Busch-Vishniac[12]. This book was picked because of a unique philosophy of coverage of the theory of sensors and actuators. Most books in this area organize the presentation around a division of material based on end application (for instance measurement of acceleration, force, flow rate, angular position, etc.). The problem with this approach is that devices that are used in different applications might actually be based on the same physical transduction mechanism relating the electrical and mechanical domains in question. The treatment in this book concentrates on the fundamental coupling mechanism between the two domains and, additionally, does not differentiate between sensors and actuators in the process of developing the basic theory. We are in agreement with the author that the chosen treatment is more conducive to supporting extension of the knowledge gained to other sensors and actuators not specifically addressed in this course, particularly the ones based on emerging technologies.

The formal course description is as follows: *Study of fundamental transduction mechanisms of common sensors and actuators. Principles of data acquisition. Use of software tools for data interaction with sensors and actuators. Introduction to micro electro-mechanical systems (MEMS). A key component of this course will be laboratory exercises involving sensors and actuators.*

The transduction mechanisms discussed in detail in this course were: a) those based on changes in the energy stored in an electric field, b) those based on changes in the energy stored in a magnetic field, and c) linear inductive transducers. Other mechanisms such as those based on changes in energy dissipation, piezo and pyro electric transducers, and optomechanical transducers were given lighter treatment due to time constraints. The above selection was based on the importance of the various mechanisms to the mechatronics area.

3.5 Capstone Project

The capstone project required the assumption of a problem that would involve incorporation of a sensor or actuator not directly covered in the lectures or laboratory activities; this directly addressed the lifelong learning feature of the course outcomes. Furthermore, the problem had to relate or connect with a real-world application. This was the most rewarding part of the course in terms of results. There were a total of four projects developed by student teams, all of which worked successfully. In addition to demonstrating the hardware, a comprehensive report and oral presentation were required at the end of the term. Details of the projects are provided below because they most effectively validate the success of the course.

a) Mobile robot follower: The objective of this project was to demonstrate the concept of "vehicle platooning". A small robotic cart with two regular wheels and a caster wheel was used. The two regular wheels were driven using separate stepper motors. A set of two infrared sensors were mounted in the front of the vehicle suitably angled to cover the space ahead. The objective was to get the vehicle to follow a target (in this case a cardboard plane) at a fixed distance. The infrared sensors provided information on the distance of the target. This information was used in a simple control algorithm to command the stepper motors to turn the wheels forward or backward as needed to maintain target distance. Figure 3 is a picture of the arrangement which was successfully demonstrated.

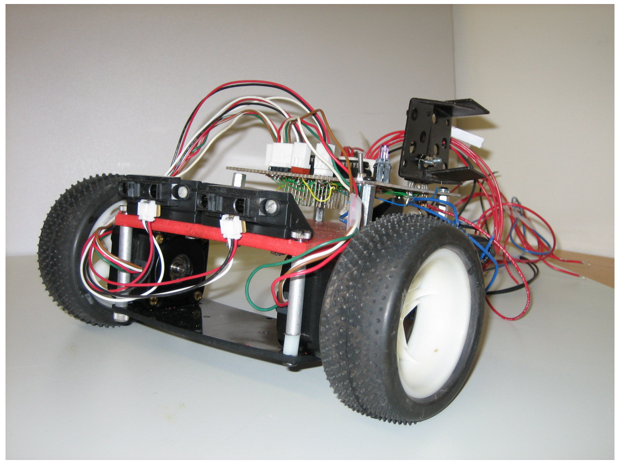


Figure 3: Mobile robot follower

b) Automated windshield wiper system: This project connects with the automated systems that have started to appear in some high end automobiles whereby the sweep rate of the windshield wipers is set based on the wetness of the windshield (as established by the volume of rain). Figure 4 shows a picture of the scaled down mockup that was constructed to represent the above application. An optical sensor enables the wetness of the windshield to be assessed through changes in the scattering of light, while a servo motor is used to actuate the sweep of the wipers. Once again a control algorithm is written in LabVIEW that uses the wetness of the windshield (altered during testing by intermittent squirting of water onto it) to establish the wiper sweep rate.

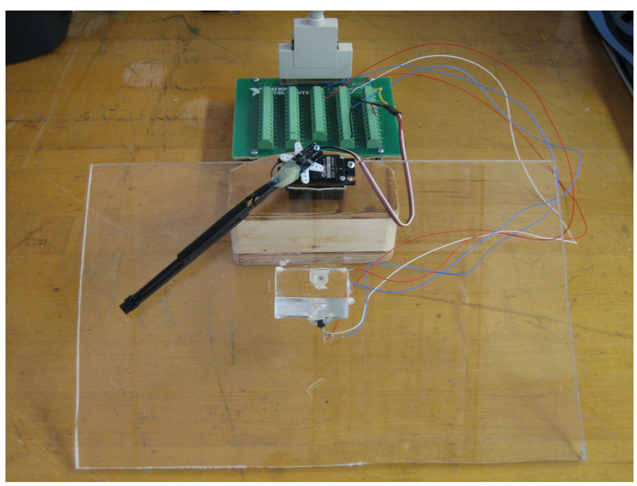


Figure 4: Automated windshield wiper system

c) Determination of object position using force sensor based triangulation: A set of three MEMS force sensors are placed under the three legs of a miniature table-like structure made using Plexiglas and short stand-offs as shown in Figure 5. The idea is to use the three force readings and appropriate interpolation algorithms to locate the point of application of a force on the table top. This project relates to techniques used to electronically determine “hits” in archery and other target-based sports.

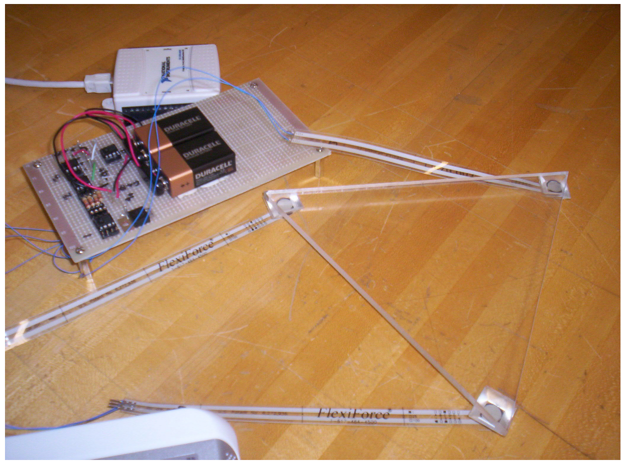


Figure 5: Locating point of application of force through interpolation of force sensor readings

d) A security system using pyroelectric sensors: The pyroelectric sensor is capable of detecting body heat and when suitably mounted on a servo motor (see Figure 6) it enables scanning of a physical space to be accomplished. The data from the sensor is processed to detect the location of the source of heat. A webcam mounted on a second servo motor is then made to point in the direction of the "intruder" whose picture is then captured.

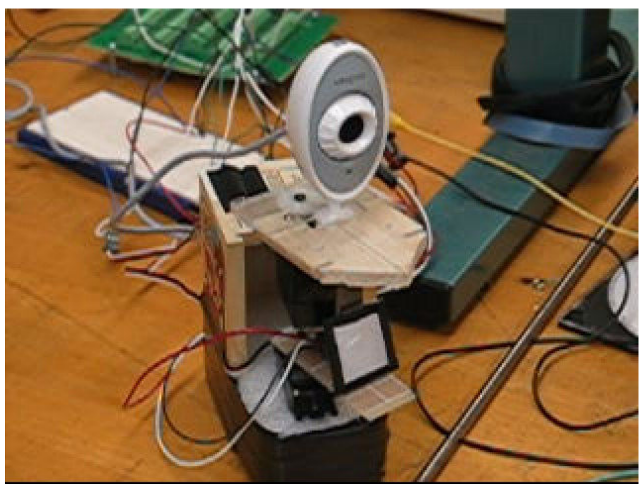


Figure 6: Security system using a pyroelectric sensor

4. Course Assessment Process

The course evaluation was conducted by an assessment expert from the Department of Psychology (who is also a co-author of this paper). The assessment tool consisted of pre- and post-course surveys followed by a comparative analysis. In addition, a faculty panel evaluated the final report and oral presentation of the capstone project. The questions posed in the surveys were developed collaboratively between Engineering faculty and the assessment expert and were conducted online. A selected subset of survey questions asked and the student responses are shown in Figures 7-14. A discussion of the results follows the data.

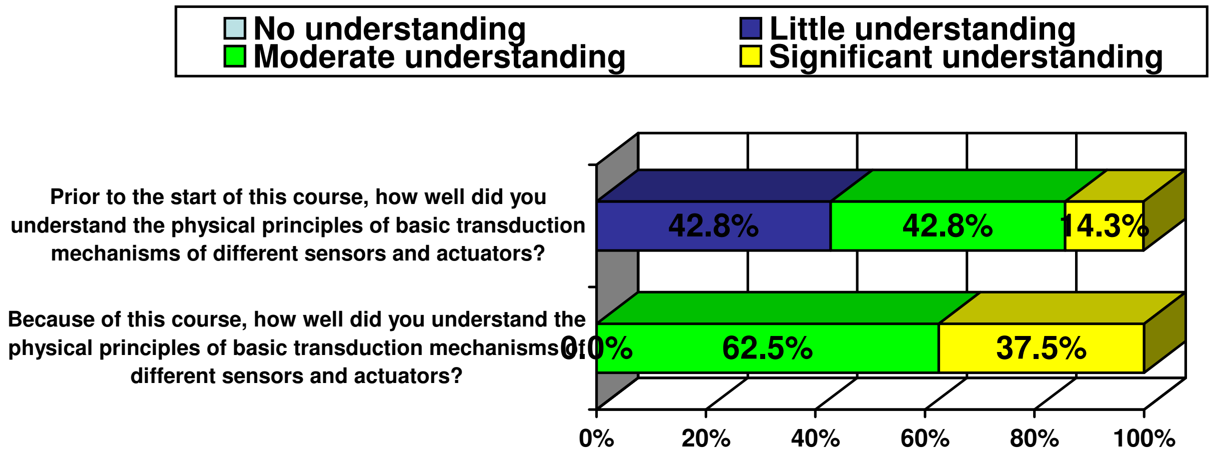


Figure 7: Assessment Data – Part 1

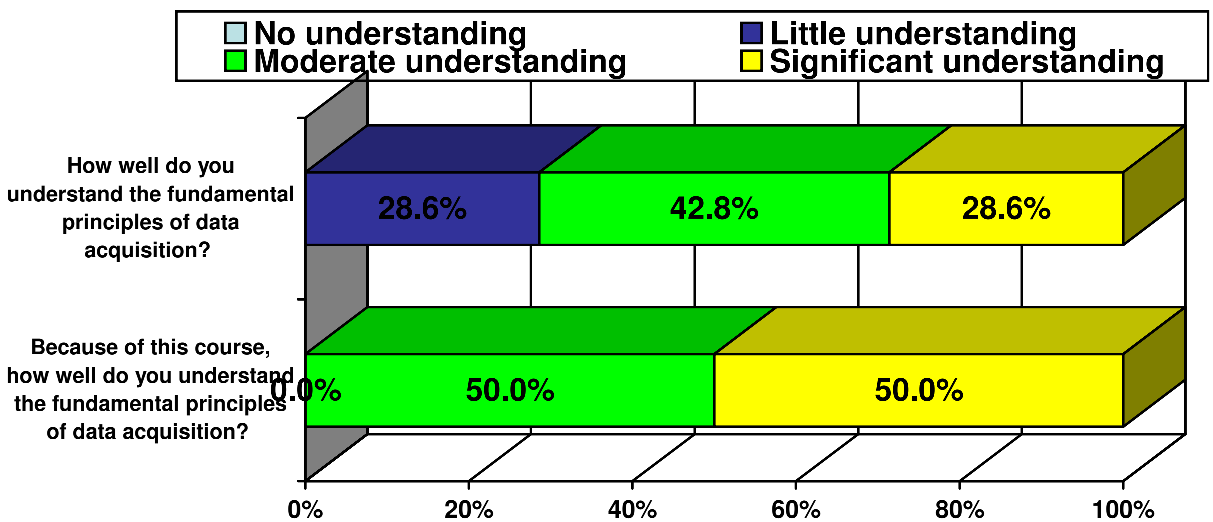


Figure 8: Assessment Data – Part 2

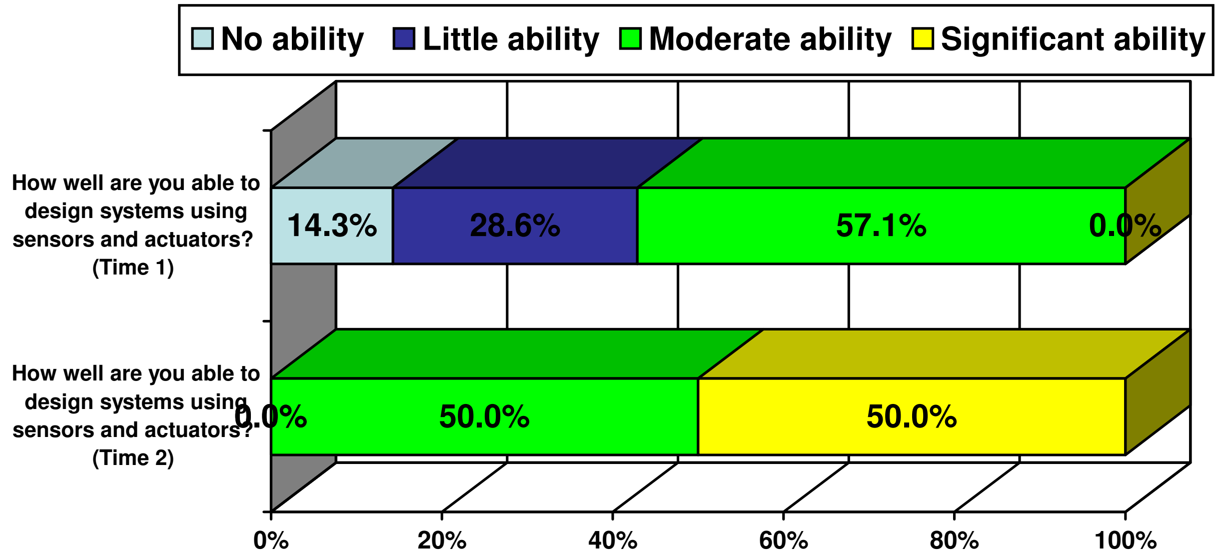


Figure 9: Assessment Data – Part 3

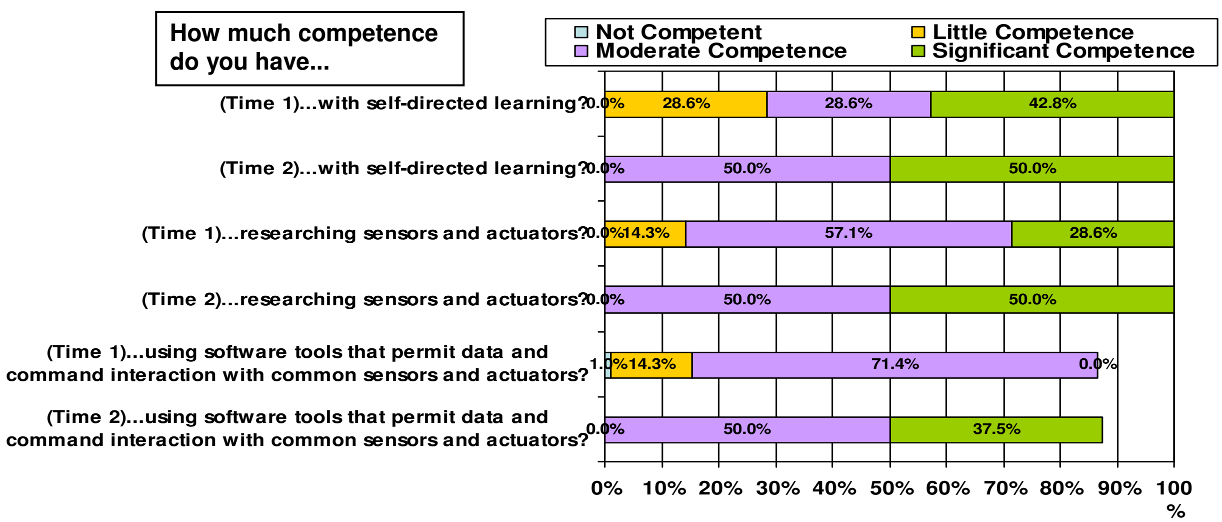


Figure 10: Assessment Data – Part 4

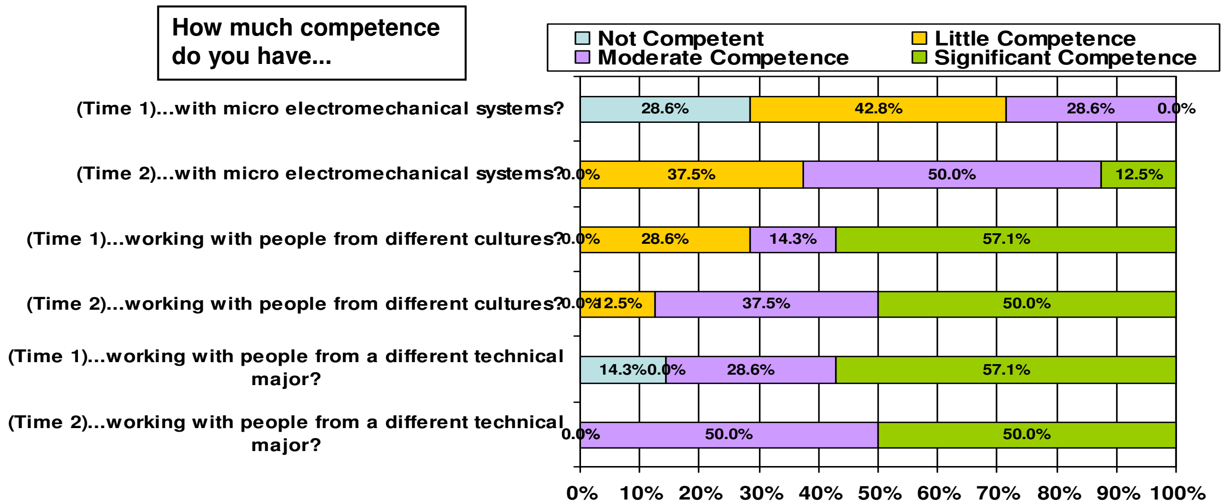


Figure 11: Assessment Data – Part 5

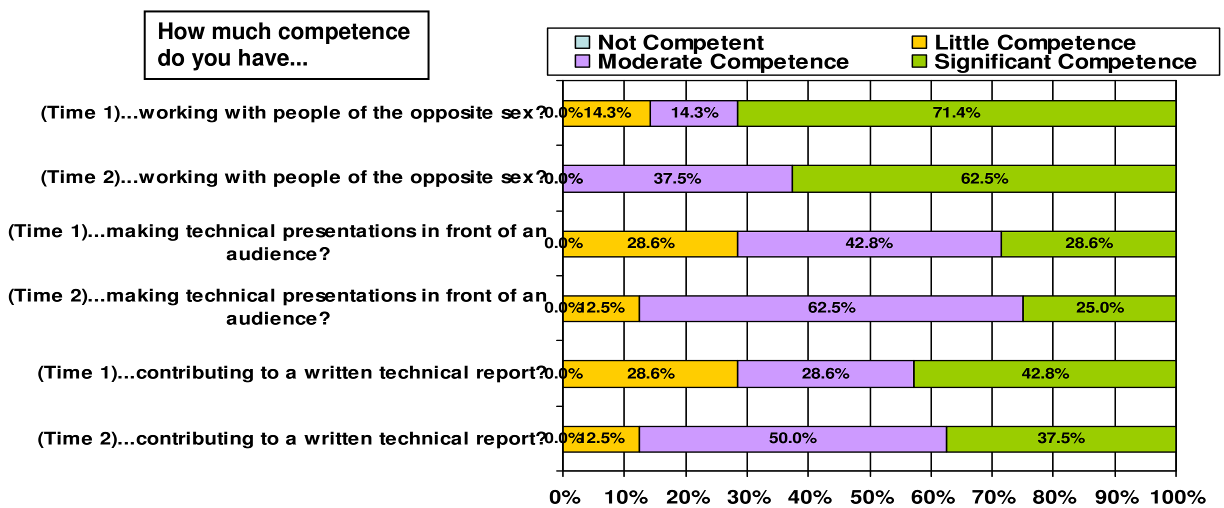
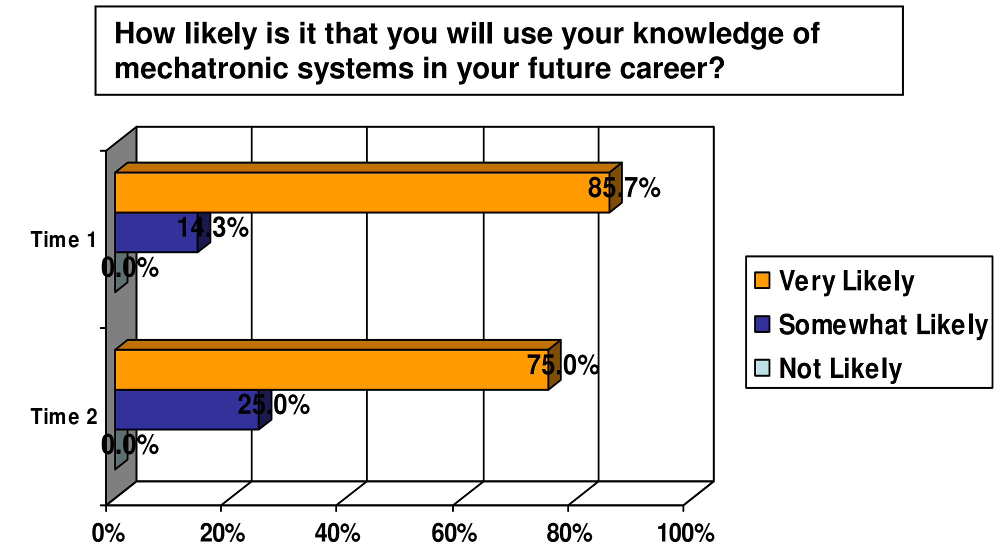


Figure 12: Assessment Data – Part 6



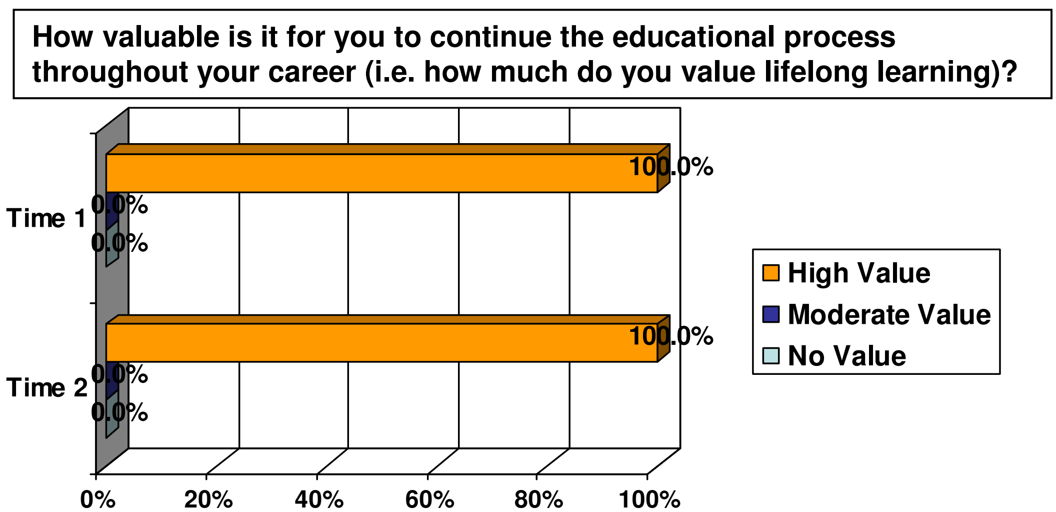


Figure 13: Assessment Data – Part 7

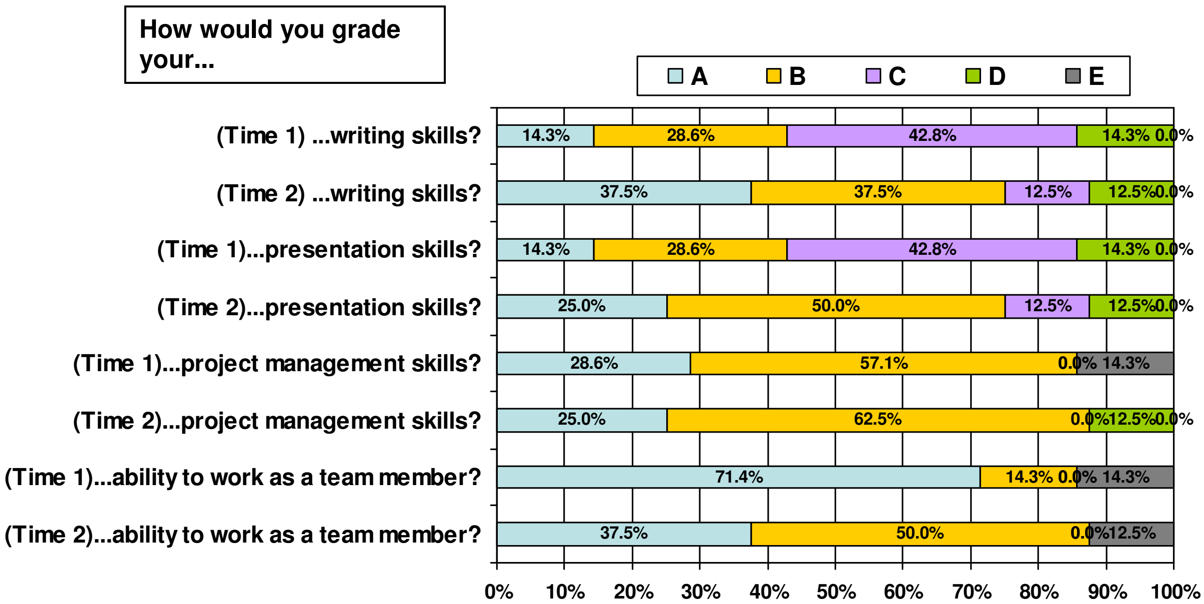


Figure 14: Assessment Data – Part 8

The results presented in Figures 7-10 (as well as the first item in Figure 11) represent the pre- and post-course student responses to questions about their mastery of the fundamental theory and applications presented in the course. It is in these areas that the most significant gains were achieved by the students. All of students who reported in the pre-course survey that they had little or no competence in these areas reported that they had moderate or significant competence by the end of the course.

The reported increase in confidence in self-directed learning (Figure 10) was especially satisfying, and was further confirmation that the capstone experience was the appropriate vehicle for achieving the course outcomes.

On the items relating to more general social and communication skills (Figures 11 and 12), the course did not seem to make much impact, at least in the students' own minds.

5. Summary

The second of two courses whose development was funded by an NSF CCLI grant has been described. The courses address a critical need in the development of mechatronics systems, a multidisciplinary area of increasing importance in products and processes in engineering, particularly in the automotive industry. A major aspect of the course construction was to supplement theoretical treatment of sensors and actuators with laboratory exercises that required working with actual devices in extended sessions outside the classroom. Furthermore, the course required a capstone project that mimicked a real world application to be completed, involving the use of a sensor or actuator not discussed in class. This aspect of the course, in particular, was a major success story. The assessment results are very positive. Efforts are underway to incorporate the course development efforts in the area of mechatronics into a new concentration or minor at both undergraduate and graduate levels.

Acknowledgement
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