Mechatronics Experiential Learning for Broadening Participation in Engineering

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Abstract

The theme behind this research is equalizing educational opportunities that lead to increased retention of students from groups that are underrepresented in engineering. Hands-on learning experiences are known to increase student engagement in their engineering training and the goal here is to make this motivator more available to underrepresented students. The motivation for this work is to improve the performance of underrepresented groups in robotics competitions. Thus the initial implementation of this work is done in the undergraduate Introduction to Robotics course. The key assessment is to examine whether students use the information they have learned in later courses, specifically the Mechanical engineering senior design course, and also within the student competition teams. This paper presents the initial attempt at this endeavor and an analysis of the assessment data collected so far.

1 Introduction

The goal of this project is to introduce a mechatronics experiential learning element into the curriculum of the Department of Mechanical and Aerospace Engineering (MAE) at the University of Texas at Arlington (UTA). This type of hands-on experience is known to motivate students, particularly those from underrepresented groups, in their study of engineering. Dr. Bowling became aware of this when he was faculty advisor for a team of students who entered the Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) Exploration Robo-Ops competition. The students were required to build a Mars rover, which would be transported to the rock yard at the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) and teleoperated from UTA. The students' enthusiasm was high, especially after attending the competition, even though we did not perform that well. It became clear that the typical UTA students' skill set was insufficient for them to truly compete. The students relied on faculty too heavily to bridge the gap between their

skill set and that required to effectively compete. This skill gap fell mainly in the mechatronics arena. Thus, even though several students were motivated to do better next time, the fact that it repeatedly seemed that other teams were much better prepared to compete was demoralizing for some students.

Some students are more sensitive to this type of experience than others, especially those from underrepresented groups. The UTA team has consistently included students from groups underrepresented in engineering, Women, African, and Mexican American students, comprising about 3/4 of the team. From Dr. Bowling's observations, students from other teams are mainly from the majority population. Performing poorly in this type of situation touches on a host of stereotypes that is not encouraging for underrepresented students. Although it is not necessary to win every competition, it is necessary that the cause can be traced to a poor design or some other technical flaw related to the students' decisions, as opposed to poor educational preparation or work done and decisions made by the faculty advisor. This is because students have control over their design and technology choices, but cannot do much about the MAE curriculum and have difficulty countermanding the advice of the faculty advisor.

Thus the authors embarked on a plan to remedy two issues with this situation:

- the reliance on faculty to bridge students' skill gap,
- the inaccessibility of a pathway through the curriculum that allows students to build their skills to the level these competitions require.

Addressing the first issue requires the faculty to download their knowledge to the students in a more formal way, other than individual coaching. Although it is reasonable to individually coach a student or students, it is troublesome when a team's performance in a competition depends on it. First, in individual coaching the faculty advisor can have undue influence over the student's decisions and choices. Secondly, if it becomes clear that the student is having undue difficulty with the task, there is still an implied obligation for the faculty advisor to help the team complete the task. This creates a difficult situation for students and faculty. The remedy for both of these issues is to incorporate the required knowledge in a regular course that all students can access.

MAE students at UTA obtain the skill set required for these types of competitions through summer internships, extra curricular research, self-motivated learning, or individual instruction. This is not a reliable way to ensure that the students who want to be involved in the competition can acquire the skills they need to be competitive. Including the required instruction in a regular course allows equal access to all students. Students may then organize themselves to complete various tasks depending on the skills they are most comfortable with. In this way, the experiential mechatronics instruction enables underrepresented students' access to a motivator that can bolster their enthusiasm for engineering. Because the competitions are focused on robotics, this initial work is focused in the undergraduate Introduction to Robotics course, which is taught by Dr. Bowling; Dr. Shiakolas teaches the graduate robotics course.

This paper presents the initial implementation of mechatronics instruction in the undergraduate robotics course. The effect of this instruction is assessed by examining whether students who take the course use the knowledge gained in later courses or student competitions. The assessment for this project is the year-long Mechanical Engineering (ME) senior capstone design course. In the senior design course, students give midway and final design presentations, which are open to the public. The authors attend these presentations to determine whether their cohort of students use the mechatronics knowledge gained in later courses. In addition, Dr. Bowling is still faculty advisor for the student competitions, which allows him to observe who is performing the mechatronics aspects of the project, and to what extent the quality of their work contributes to the success, failure or otherwise in the competition. Dr. Shiakolas is also the faculty advisor for a senior project group that focuses on the design, fabrication and demonstration of a robotic hand, which can be used as an end-effector or a prosthesis. This access allows him to observe the students' effectiveness in applying mechatronics to successfully address this problem. Admittedly, the cohort of students examined herein is small, but these observations still give a positive view of how this type of instruction can broaden participation of underrepresented groups in engineering. Observations based on this small cohort are presented and discussed, after presentation of the instructional approach.

2 Background

Reports abound indicating that minorities and women are underrepresented in STEM fields, a result of decreased initial enrollment and retention rates^{17;36;65}. In the first chapter of their work, Burke and Mattis discuss numerous reasons for the decreased representation of women, such as lack of encouragement, decreased interest after high school, increased chance to switch out of STEM, and a significant preference for biological sciences over physical sciences and engineering²³. Several other studies support this gender correlation^{26;77}. In considering the underrepresentation of minority students, several causative factors have been identified: decreased exposure and awareness of science²¹, pre-college preparation⁸², financial assistance⁶², and prior experiences and achievement in mathematics and science^{6;31;37;64}. Retention for both minorities and women has also been linked to availability of role models from these underrepresented groups^{5;25;73}.

This work proposes that increasing engagement through experiential learning can also increase the number of underrepresented students entering and remaining in engineering. A large body of work exists examining student engagement and learning at the college level^{40;70}. Student engagement is described as a multidimensional phenomenon including at least some behavioral and affective components. It significantly improves students' ability to learn course concepts and recall information⁶³. While many argue that engagement and motivation are rooted in individual cognitive skills, several authors recognize the importance of classroom experience in shaping one's dispositions toward education and learning.

Active, participative and experiential learning have been proposed as methods for increas-

ing student engagement. They include techniques such as speaking activities, discussions, case-studies, concept tests and anonymous voting, and hands-on experience-based problem solving^{41;48}. While experiential learning techniques date back millennia, modern theory has been developing since the 1970's, led largely by Dr. David Kolb; this theory is based "on a learning cycle driven by the resolution of the dual dialectics of action/reflection and experience/abstraction"⁴³. The importance of experiential learning has been discussed for the medical field^{1;3;9;15;18;33;61}, engineering^{2;19;76;84;85}, leadership roles^{16;29;32;34}, and general education^{7;58;86;87}. For further reading on broad applications of the experiential approach, Kolb has compiled bibliographies containing numerous works spanning decades^{44;45;46;47}.

Burger found that experience with actual work is one of the strongest factors affecting career choice²² while Tuss concludes that "experiential education strategies will strengthen school science performance, particularly among students from underrepresented groups"⁸¹. In a study similar to this work in which the cohort were students and faculty participating in the Malaysian ROBOCON 2010, Ayob found that "students' creativity dimensions have been nurtured and enhanced as a result of the problem solving process involved in the experiential learning activities"⁸. Verner and Ahlgren discussed the hands-on experience gained by junior-high and high school students while designing and building robots for a Trinity College Robot Contest⁸³. Hall discusses how a curriculum at Louisiana Tech University designed to boost experiential learning by putting the ownership and maintenance of the robotics equipment into the hands of the students has shown large gains over previous curricula³⁹. Jara found that students in Automatics and Robotics at the University of Alicante significantly improved their efficacy and performance following a "learning by doing" approach using a remote robotic laboratory called RobUALab⁴². Cannon positively reviewed a University of Minnesota robotics day camp for middle school youth designed to inspire minorities and women to pursue careers in STEM through hands-on learning²⁴. This work aims to provide additional support for these findings.

This work is based on the hypothesis that in addition to engagement, the proposed approach will also positively affect students' academic success by boosting self-efficacy, the perceived ability to complete a task and reach a goal. Self-efficacy has been proposed as a key component in a unified theory of behavioral change¹¹. This concept has been linked to general education and cognitive success in numerous fields^{12;13;14;20;50;51;56;74;75;88}. Various works have linked student's efficacy to academic success specifically with respect to race, gender, and collegiate-level STEM courses^{4;10;27;28;30;35;38;49;52;53;54;55;57;59;60;71;72;79;80;89}. Criticism of pedagogies centered on self-efficacy have suggested that when studied, the effect of social inequities leading to poorer academic performance are hidden⁷⁸.

3 Instructional Approach

Previously the Introduction to Robotics course focused on modeling the dynamics of robotic systems and how this dynamic analysis could be used to design and control robots. The effort in this work is to allow students to put these theories into practice on real hardware

systems in an instructional environment, and to gain other practical knowledge required to realize an actual mechatronic system. This gives students a foundation that facilitates their application of these ideas in other situations, such as building a Mars rover for a student competition or the projects they choose in their capstone senior design course. In this work Dr. Bowling was responsible for the theoretical portion of the instruction, and Dr. Shiakolas was responsible for the experimental portion.

3.1 Theoretical Instruction

The analysis of robot dynamics and control taught in the undergraduate robotics course follows the schematic in Fig. 1. Most of the modules in Fig. 1 have a design or control aspect to them that is emphasized during the course.

Position and Orientation: This module discusses points, directions, and reference frames, and how they are used to compose a description of position and orientation described by position vectors and rotation matrices. These constructs are used to build a description of the position and orientation of the robot's end-effector. The design elements discussed include visualizing the workspace of the robot's end-effector in order to choose the number of links and the physical layout of the robot. Constraints on the robot's kinematics are also discussed, which leads to a discussion of the interaction between motors, gears, and links.

Linear and Angular Velocity: Differentiation of position and orientation yields descriptions of the robot's translational and rotational velocities. The design and control aspects discussed in this module are associated with the definition of the *Jacobian*, which describes the velocity of the end-effector, the singularities associated with movement of the end-effector, and how the Jacobian can be used in model-based control. In particular, the use of the Jacobian in *operational space control* is discussed.

Linear and Angular Acceleration: The descriptions of velocity can be differentiated to obtain the accelerations needed to develop the equations of motion.

Masses and Inertias: In this module the mass distribution is discussed. This includes a discussion of the composition of a motor, the rotor and stator, and the moments of inertia associated with the rotor.

Forces and Moments: Here the generation of torque in the motor, between the rotor and

Figure 1: Theoretical Developments.

stator, is presented. This includes brief discussions of the rotor, stator, and the magnetic field that generates a torque between them. The manner in which the motor torque is included in the equations of motion is also discussed.

Equations of Motion: The derivation of the equations of motion shows how many of the robot components come together to produce motion. A key element to discuss here is the *reflected inertia* that appears in the mass matrix, which is related to the gear ratios and the moments of inertia of the rotor. The trade off between motor torque amplification, through gearing, and the reflected inertia is discussed. Simulation and animation of the predictions obtained from the equations of motion is also discussed.

Control: Model based control, particularly the computed torque method and operational space control, is discussed along with trajectory generation. Simulating this controller for a desired trajectory allows students to produce motor speed-torque curves. These estimated speed-torque curves can then be used to size the actual motors for the real robots they are attempting to build.

Thus in the Introduction to Robotics course they are taught several theories that they can use to assist in the design of a robot. Providing this information in a classroom setting that is equally accessible to all students allows them to self-select for positions on a competition team where they feel most confident in their own abilities. This is in contrast to students randomly, or through their own interest, choosing tasks that they have no idea how to accomplish, and then relying heavily on the faculty advisor to help them complete the task.

3.2 Experiential, Hands-On Instruction

The experiential hands-on instruction component of the course was focused on assembling and controlling a two-link planar robotic manipulator. Students were introduced to the software tools and hardware components that would enable them to apply concepts learned in the theoretical component of the course to the two-link manipulator problem. MAE students do not receive formal instruction in mechatronics except for a basic introduction to software-hardware interfacing in one laboratory exercise in a junior/senior level course taught by Dr. Shiakolas. His familiarity with the students' background in mechatronics was important in selecting the appropriate software and hardware tools for improving the undergraduate robotics course.

Available environments from National Instruments (NI), MathWorks, Quanser, Wolfram and others were considered. The selection criteria considered Dr. Shiakolas's experiences with the students in regular and laboratory courses and advising in senior design projects, as well as required courses on programming or experimentation in the undergraduate mechanical engineering degree plan. The selection criteria were dominated by ease of:

- integration and interface of software and hardware components
- programming

- visualizing program and information flow
- developing graphical user interface to interact with selected hardware
- developing graphical user interface to display the status of the hardware
- modifying, re-using and expanding a developed or existing program
- modifying control parameters and variables interactively
- connecting, interfacing and interacting with the hardware
- using or re-using available libraries of course ware, tutorials, and educational resources and other specialized software modules or functions provided by the manufacturer
- teaching multiple concepts using the same software and hardware components
- access to online resources and tutorials that would allow the students to quickly become familiar and comfortable with the selected tools

The criteria considered for resource availability were examples and exercises provided by the manufacturer that could be easily modified, and used by the students and availability of company sponsored forums where students could post questions and get timely answers. The NI systems met all of these criteria and have been successfully employed for pedagogical and instructional purposes.

The software tools employed were the resources available in the standard LabVIEW suite and the NI myRIO software modules⁶⁶. The major hardware resources used for the experiential learning component were the NI myRIO, a reconfigurable input output real time controller, the myRIO Starter kit with basic sensors⁶⁹, and the myRIO Mechatronics kit with sensors and actuators⁶⁷. Other hardware included computers and peripheral electrical components such as a multi-meter, cables and wire cutters. The twelve students enrolled comprised six laboratory groups of two students per group. Each group was assigned a project toolbox containing one myRIO, one Starter and one Mechatronics kits and peripheral hardware as shown in Fig. 2. The students had access to the project setup and toolbox in the laboratory while the teaching assistant was available. The groups also had the option to check-out their toolbox and work with it at home or outside the lab at their own pace, which was well received and taken advantage of by the students.

Lectures devoted to discussing the overall concept of mechatronics and introducing the overall LabVIEW software environment were also incorporated in the Introduction to Robotics course. The first lecture discussed a simple LabVIEW Virtual Instrument (VI) was developed to explain the Front Panel (FP) and Block Diagram (BD) windows, and the manner in which these tools could be used to develop a controller for the two-link planar robot. A second lecture was devoted to introducing the myRIO hardware and programming procedures, as well as the sensors and actuators in the starter and mechatronics kits. In addition, the NI myRIO Essentials Guide⁶⁸ was discussed and the features in this guide were explained.

Figure 2: MyRio Mechatronics Kit from National Instruments.

The initial exercises assigned to the students were based on the starter kit hardware and the instructions in the essentials guide. The students selected at least five sensors with which to explore data acquisition. These exercises introduced the students to the operation of various sensors, and sensor connectivity, as well as breadboards and simple circuitry. This exercise gave them an understanding of the concepts of analog input, signal definition, and sample rate for a data acquisition device (range, min, max, bits). They learned how to interface a sensor to myRIO in order to acquire, process, modify, and display sensor data. In addition, the students experimented with VIs to further familiarize themselves with the software. The students were introduced to the concepts of filtering, including filter characteristics and implementation using LabVIEW modules or toolboxes.

The next set of exercises were based on the mechatronics kit using the essentials guide. Students were explained the differences between a DC and a servo motor. Experiments were aimed at understanding and mastering motor control. An important concept in motor control, pulse width modulation (PWM), was introduced and the students experimented with a PWM based controller to control the angular rotation of the shaft for one motor. The students modified the VI and experimented to understand the importance of PWM parameters of frequency and amplitude as well as PID controller gains.

The two degree-of-freedom (DOF) manipulator, shown in Fig. 3, was constructed using two servo motors found in the mechatronics kit. Two links were designed, one connecting the two motors and one holding a pencil for end-effector. The connecting link could be attached at various locations, changing the distance between the two motors and consequently the inertial properties of the system and the equations of motion. The end-effector link was designed to allow for the end-effector to be attached at various locations relative to the motor, affecting the forward and inverse kinematics, and slightly changing the inertial properties of the system.

Figure 3: Two DOF Manipulator Laboratory Setup.

The students were instructed on the use of scripting features such as MathScript or formula node in LabVIEW in order to develop a modular and easily modified inverse kinematics solution for the two joint manipulator considering constraints on the angular rotation of the motors similar to an industrial type planar robot. In the implementation they were able to easily modify the kinematic structure based on the attachment locations of the links. The students verified their inverse kinematics algorithm in a simulated environment by defining link lengths, an array of desired end-effector locations, and obtaining the corresponding solution sets. Students also animated the robot's kinematics using LabVIEW graphing tools.

The students then developed the interaction environment for controlling two motors independently.

4 Assessment

The main assessment of this project was based on examining the effect of the mechatronics instruction on the students after they complete the course. The main course we wanted to observe was senior design in Mechanical Engineering, which the students can take after or concurrently with the Introduction to Robotics course. The goal is to determine if they would use their knowledge in projects that involved mechatronics or would they avoid those projects altogether. If students chose to engage in mechatronics projects this should indicate some affinity toward mechatronics and some confidence in their ability to carry out the required work. In addition, there was an effort to survey students to find out where they are obtaining their instruction in mechatronics.

The assessment of the senior design course was based on an evaluation rubric that scores the level of mechatronics in a particular project. This scoring was based on attending the mid-way reports for the senior design projects. These presentations are open to the public so the authors could sit in the back and score the projects without anyone, especially the students, knowing what was being done. The students

Table 1: Participation Evaluation Rubric.

Project ₁	Existence	Involvement	
	#	R	U
S	#	3 (1)	2 (1)
M	#	3 (1)	2 (1)
D	{ 0, 1 }	3 (1)	2 (1)
F	{ 0, 1 }	3 (1)	2 (1)
C	{ 0, 1 }	3 (1)	2 (1)
I	{ 0, 1 }	3 (1)	2 (1)
total	$a = \sum$	# unique b (c)	# unique d (e)
score	a	$b*a$ ($c*a$)	$d*a$ ($e*a$)

R - represented students U - underrepresented students

were not told before or after the presentations about the scoring done by the authors. The scoring rubric is shown in Table 1. The key aspects of mechatronics we want to measure involvement in are: 1) choosing sensors (S), 2) choosing motors (M), 3) development of data acquisition system (D), 4) choosing and programming filtering and signal processing hardware and software (F), 5) synthesizing motor control (C), and 6) overall system integration (I).

The existence column indicates whether the elements existed in the project, for example how many sensors and motors were used, and the remaining rows receive a 1 if the element exists and 0 if it does not. The sum of these scores is labeled “a” in Table 1. The Involvement column indicates how many students were involved in the activity, with the number who took Introduction to Robotics in parenthesis for represented and underrepresented students. The number of unique students in each category is summed to obtain a total; if the same student was involved in all categories they would only be counted once. The student totals are multiplied by “a” which gives a score for the project. *A high score indicates a large number*

of students involved in a highly mechatronic project, and allows us to determine whether involvement of mechatronics in Senior design is increasing.

The cohort in this first offering of the new course was composed of twelve males consisting of four White, two Hispanic, and one African-American student, with the other five being of unknown or International origins. The African-American student had a focus in Aerospace Engineering so was not involved in the Mechanical Engineering senior design course. Thus the main interest was in the Hispanic students because of the focus of this project on broadening participation in engineering.

5 Data Summary and Discussion

The 2014 Fall semester senior design course had 59 students divided into thirteen groups. The presentations were meant to be midway progress reports. Mechanical engineering capstone senior design is a two consecutive semester course, with a midway presentation at the end of the first semester. Every student in the group had to present and each told of the portion of the project for which they were responsible, so it was possible to discern who was working on the mechatronics aspects if any. Three of the thirteen projects, 23.1%, involved elements of mechatronics, whose scores are given in Table 2. This shows that approximately 77% of the students did not pursue projects involving mechatronics.

Table 2: Scores for Mechanical Engineering Senior Design Projects.

Project	Existence	Involvement	
		R	U
3	3	1 (0)	0 (0)
4	10	30 (10)	0 (0)
12	8	16 (8)	16 (8)

R-Represented U-Unrepresented

Table 3: Observations on Mechanical Engineering Senior Design Projects.

	Mechatronics			
	Involved		Not-Involved	
	Cohort	Non-Cohort	Cohort	Non-Cohort
Underrepresented	1	10	1	10
Represented	3	4	0	30
Total	4	14	1	40

The project scoring highest in mechatronics did not involve any underrepresented students, but did include one student who was taking the Introduction to Robotics course concurrently with senior design. This student was working on the filtering and signal processing aspect of the project, which was taught in the course. The second highest scoring project involved two students who were concurrently taking the Introduction to Robotics with senior design, one of which was from an underrepresented group.

Table 3 gives a breakdown of the number of students in the Mechanical Engineering senior design course. The data shows that there were four students from the cohort that were involved in mechatronics projects, one of them from an underrepresented group. However,

the more interesting information in Table 3 is that 22 of the 59 students in the course, approximately 37%, are from underrepresented groups, and of that number 50% are involved in mechatronics projects. In contrast, 23% of the students from represented groups were involved in mechatronics projects. This lends support to the idea that underrepresented students may be greatly interested in projects involving mechatronics. Thus the proposed instruction can help to increase the number of underrepresented students pursuing careers in engineering.

The students enrolled in Introduction to Robotics were also asked to complete a survey discussing course topics. Students were asked if their previous experience with seven specific areas of mechatronics was sufficient to complete the projects in the course. Ten surveys were returned and the results can be seen in Table 4. Only a small number of students expressed confidence that their previous mechatronics experience was sufficient to complete the exercises related to the two DOF planar robot. This supports the need for formal introduction of mechatronics in the curriculum, because this skill set is required to effectively compete in the robotics competitions and to successfully complete senior design projects.

Table 4: Introduction to Robotics Survey Results.

Topic	Yes	No	NA
Software-hardware interface	3	6	1
Integrated software systems	2	7	1
Data acquisition systems	2	6	2
Signal processing	4	4	2
Data filtering	3	4	3
Software control system	4	4	2
Non-software electronics	4	3	3

6 Conclusions

This work focused on broadening participation in engineering by introducing mechatronics through experiential hands-on learning in the undergraduate Introduction to Robotics course. Although this was a first small study done on this topic in the ME program at UTA, the assessment data indicates the students lack a sufficient background in mechatronics to effectively compete in robotic competitions and integrate mechatronics components in the senior projects. However, some students from the cohort are currently working on mechatronics related senior design and robotic competition projects. Because they just recently completed the Introduction to Robotics course in the Fall 2014, further observation is required to assess the students confidence and ability to apply the acquired knowledge. The authors will continue monitoring the cohort in the capstone design course and robotic competition until the end of the spring 2015 semester and report their findings in a subsequent publication. However, the authors are confident the number of underrepresented students interested in obtaining formal, hands-on mechatronics experience will increase in subsequent offerings of the course, and that it will bolster their confidence in applying mechatronics in curricular and extracurricular activities. This ability will increase their excitement with, and desire to remain in engineering, thereby broadening participation. The cohort can then demonstrate

these abilities to current and prospective underrepresented college or K-12 students, possibly increasing the number of students choosing STEM fields.

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