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Implementing Problem-Based Learning in a Senior/Graduate Mechatronics Course

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Introduction

Active learning requires students to discuss issues or work problems in the classroom, rather than listening passively to a lecture. If students informally assist one another in this process, the technique is deemed to be *collaborative learning*. If formal structures exist to guide student interaction, the process is considered *cooperative learning*.[1,2] A related approach, *problem-based learning*, introduces engaging real-world problems for students to solve, usually as part of a group.[3] Lawrence Technological University (Lawrence Tech) has been engaged in a six-year process to incorporate active and collaborative learning (ACL) and problem-based learning (PBL) in its undergraduate engineering curriculum.[4,5] This paper details implementation of PBL as a half-semester design problem within a graduate-level mechatronics course at Lawrence Tech.

Much of the structure for the Lawrence Tech offering is derived from a graduate-level course in mechatronics that both authors have taught separately for Purdue University's School of Mechanical Engineering (Purdue). The authors share a doctoral advisor, who developed the original course at Purdue. As colleagues in both research and teaching, the authors have engaged in frequent collaboration regarding instruction in mechatronic design. While the pairing of a small, private university with a large, public university is unusual in regards to student populations, the authors used common lecture materials and laboratory experiments to minimize differences in student populations. Differences in student response to the PBL implementation are expected and further work will be needed to analyze those differences.

An emphasis of the Purdue course is that students must construct an automated device, integrating prior knowledge regarding mechatronic systems components. In the past, the Purdue projects have not been based on real-world problems. Thus, the authors have experience instructing mechatronics in the absence of a PBL activity. This article describes student reactions to incorporating PBL into the Lawrence Tech course. Future work will incorporate PBL into Purdue's course to generate additional data, albeit from public research university rather than a private teaching university.

During the first half of the mechatronics course, students are exposed to traditional lectures and lab experiments. In the second half of the course, students work collaboratively to design and build an automated device. It was hypothesized that reformulating the design project as a problem- or project-based learning activity would facilitate long-term learning among undergraduate as well as graduate students. It is intended that the design problem serve two purposes: a) encourage students to apply knowledge from the lab assignments, and b) allow students to learn the value of integrated mechanical-electronic-software design as compared to the more conventional process of sequential design. The first goal, application of prior knowledge, makes the activity more similar to a project-based learning approach while the second goal, new learning, makes the activity more similar to a problem-based learning approach.[6]

This paper is organized as follows. First, the mechatronic design process is explained. Then the Mechatronic Systems Engineering degree program at Lawrence Tech is introduced. Next, the course structure is defined, followed by a description of how the PBL activity was implemented for this study. Finally, the PBL activity is evaluated and the work is concluded.

Mechatronic Design

Mechatronics is characterized by an integration of mechanical, electronic, control, and computer systems. This is shown schematically in Figure 1. Mechanical elements may include thermal or fluid systems, solid mechanics, dynamics and vibrations. Electronic components may include sensors, actuators, power systems, and communication systems. Control methodologies (such as digital logic and feedback theory) may be used to direct device actions. Computer systems may include the use of computers in the design phase, as well as integrating microprocessors into the final product. At the undergraduate level, these mechatronic components may appear in Mechanical Engineering, Electrical Engineering, or Computer Science degree programs. The study of mechatronics is, by nature, interdisciplinary.

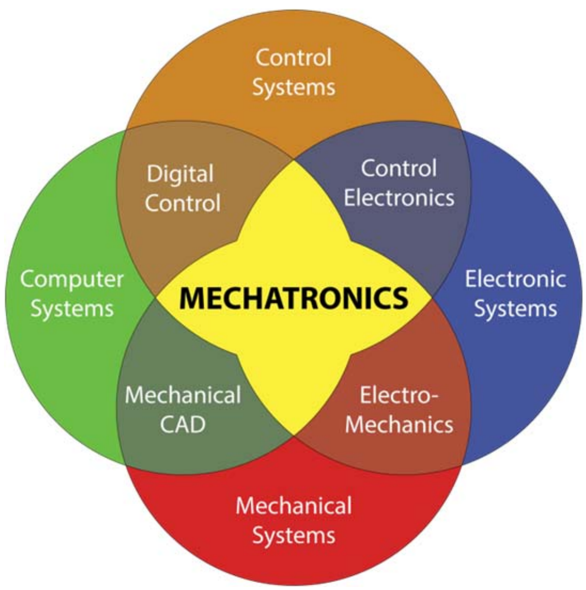

Figure 1. The interdisciplinary nature of Mechatronics.

A conventional sequential design might require a mechanical engineer to develop the mechanical design in advance of asking an electrical engineer to integrate necessary electronic components. Once mechanical and electronic designs are finalized, a programmer might then be required to invoke desired device actions and responses. While each step of this sequential process may produce the best design then available, limitations imposed by decisions at prior steps preclude any guarantee that the overall design will be optimal.

In contrast, integrated mechatronic design seeks to use a combination of the four components in a parallel design process. For example, consideration of the sensor, actuator, and software needs during mechanical systems design can result in a better overall design. However, to be capable of participating in a parallel, interdisciplinary design process, the mechatronics engineer must have a familiarity with, if not expertise in, each of the four mechatronic components.

Mechatronic Systems Engineering

The Master of Science degree in Mechatronic Systems Engineering (MSMSE) at Lawrence Tech is one of a very few such degrees offered in the United States. Its curriculum encompasses the four components of mechatronic design shown in Figure 1. Intended for graduate students with a Mechanical Engineering or Electrical Engineering background, the program builds on that background with courses in dynamics and vibrations, state-space control theory (including robust and digital control), integration of sensors and actuators with microcontrollers, and integration of mechatronic systems comprised of mechanical systems with controllers implemented on hardware platforms such as field-programmable gate arrays (FPGAs) and microcontrollers. In addition, students elect to either complete a thesis or enroll in two elective courses. Electives include a mix of theory and mechatronics applications.

The course described in this paper, MSE5183 Mechatronic Systems I, serves as an entry-level graduate course for students enrolled in the MSMSE program as well as a technical elective for undergraduate students in Mechanical Engineering or Electrical Engineering. For many undergraduate and graduate students, this course serves as a first experience with the integration of sensors, actuators, and microcontrollers. The half-semester design project serves to teach students the integrated mechatronic design process.

Approximately 10 students per offering enroll in Mechatronic Systems I. Undergraduate students are typically traditional students enrolled in between 12 and 18 credits per semester while graduate students are older, often have families, and work full-time while enrolled in one or two evening courses per semester. Thus, the Mechatronic Systems I student population is diverse in background, degree program, and external pressures.

Although mechatronics is taught in several of Purdue's schools (including Mechanical Engineering, Electrical Engineering, and Aerospace Engineering), the public university does not offer a degree program in Mechatronics Engineering. Nonetheless, Purdue offers a course (ME588 Mechatronics) that is identical in content and structure to Lawrence Tech's course (MSE5183). Enrollment in the Purdue course is approximately 30 students per offering. The PBL described in this work will be implemented at Purdue in Spring 2014, allowing for further evaluation on a larger student population.

Course Structure

For the mechatronics courses at both Lawrence Tech and Purdue, students are placed into lab groups of 2-3 students based on a preliminary self-assessment of personal strengths concerning course topics. These instructor-assigned groupings also weigh factors such as student degree program, course load, and work schedules. Self-assessments are not necessarily accurate indicators of student abilities; alternate means for assessing initial talents will be considered at a later time. This might include a short quiz or hands-on experiment to gauge students' prior knowledge.

A set of six structured lab assignments are used to teach preliminary concepts. Topics include an introduction to microcontrollers, discrete transistors as switches, infrared (IR) sensor integration with microcontrollers, DC motor integration with microcontrollers, and finite state machines. Shown in Table 1 is a listing of lab concepts. All concepts needed for the lab assignments (other than the microprocessor platform and associated software) are discussed in lecture materials prior to the lab period. Each lab assignment is followed with a report to be completed by the lab groups. Lab reports are brief and are intended to verify that students have acquired the needed technical skills.

Table 1. Structured lab assignment concepts.

Lab #	**Concepts Applied**
1	Introduction to lab instruments: oscilloscope, function generator, digital multimeter, DC power supply, logic analyzer
2	Arduino Uno programming, integrating switches and transistors
3	Binary counters, analog inputs, and seven-segment displays
4	Integrating analog and digital IR sensors
5	State machine design and implementation
6	DC motors: PWM speed control and H-bridge

All labs use an Arduino Uno platform that students purchase in lieu of a textbook. The Arduino Uno was selected for its ease of use, free software, and large ecosystem. Ease of use is critical for students in an introductory course; the Arduino integrated development environment (IDE) works on Windows, Mac OS, and Linux, handles hardware integration automatically, includes many sample codes and libraries, and connects to the available online language reference. Combined with the large ecosystem of existing projects, students learn by example without investing heavily in learning the language or IDE.

Although necessary, concepts covered in the structured lab assignments are not sufficient to teach mechatronic system implementation. A half-semester project is therefore used to apply the lab-related concepts while focusing on integrated mechanical-electronic-software design. Students design an autonomous vehicle that operates within a predefined arena to accomplish the given task within a specified budget and timeline. Lab groups are merged or reassigned into larger project teams of 3-4 students. At Purdue, the use of multiple lab sections allows project teams to be formed with one lab group from each lab section, increasing contact time with the lab instructor. At Lawrence Tech, this is not feasible due to the smaller class size.

Prior iterations of this course at both Lawrence Tech and Purdue utilized a collaborative project without other features of PBL such as a real-world problem. Previous projects included balloon popping, moving randomly placed tennis balls to a horizontal hole, moving randomly placed tennis balls to a vertically-aligned goal, and launching a tennis ball past a competing robot into a vertical-aligned goal. In each case, the task was clearly fictitious without connection to a real-world problem. Results of previous projects were largely positive, but students often failed to learn the value of the integrated mechatronic design approach until faced with near failure of their projects.

PBL Implementation

A real-world, humanitarian problem was developed to engage students in mechatronic design: clearing ‘butterfly’ landmines in Afghanistan. Following the first deployment of this project at Lawrence Tech, the text was updated for clarity before usage at Purdue. The revised description, which does not alter the project objectives, is provided below:

> According to a recent report [1], nearly 60 countries across 5 continents are contaminated with land mines. Each week some 20 people are killed, and another 49 injured, as land mines, cluster munitions, and other explosive remnants of war (ERW) are caused to detonate. Annual casualties are highest in Afghanistan, Cambodia, and Columbia.
>
> Your task is to design and build an autonomous robot capable of locating a particular type of land mine, and marking such mines for removal by trained experts. As part of a product demonstration, your robot is to autonomously detect and mark all dummy land mines located within a small testing area. To facilitate transportation, your robot must fit into a small packing crate.
>
> As a result of multiple armed conflicts within its borders, Afghanistan records more mine incidents than any other country, with civilian casualties totaling 562 in 2012. Children account for 61% of that number. Over two-thirds of child casualties involve munitions remaining from past conflicts [1]. More than one million Afghans live within 500 meters (0.31 miles) of a known minefield [2].

Figure 2**.** PFM-1 ‘butterfly’ blast mine.
Image: www.one-step-beyond.de/en/countries/afghanistan/mines/afghanistan_mine_pfm-1.html

> About two-thirds of the unexploded ordinance in Afghanistan dates to the Soviet Union’s intervention and occupation (1979–1989) of that country [3]. During this period, helicopter crews dropped large numbers of antipersonnel devices into the Afghan countryside; the most common device was a PFM-1 ‘butterfly’ mine. Due to its shape, this mine would flutter downward like a maple seed, its descent slowed sufficiently to prevent an explosion upon ground contact. Unfortunately,

its interesting shape enticed youngsters to view the mine as a “toy.” Because the triggering mechanism is activated by cumulative pressure on the mine’s wings, children would often play for hours before an explosion occurred [4]; hand and head traumas, often lethal, would result. Each spring, as the snowpack melts, previously hidden mines are washed down the mountains and into clearings and pastures [5]. Concerted efforts have been made to find and clear Afghan mine fields. However, the work is slow and dangerous. Deminers may be at risk of attack or abduction from armed groups, as well as facing the inherent dangers associated with mine removal. Although significant progress has been made over the last decade, mine clearing productivity in the foreseeable future will likely be constrained by reductions in funding and staffing [6].

[1] “Landmine Monitor Report 2013,” Landmine & Cluster Munition Monitor.
URL: www.the-monitor.org
[2] “Portfolio of Mine Action Projects: Afghanistan,” E-Mine, The UN Mine Action Gateway.
URL: www.mineaction.org/resources/portfolio
[3] “Old Mines Bring New Casualties In Afghanistan,” Sean Carberry, National Public Radio, July 17, 2012.
URL: www.npr.org/2012/07/17/156726006/old-mines-bring-new-casualties-in-afghanistan
[4] “The Horror of Landmines,” Gino Strada, PBS POV Documentary: Afghanistan Year 1380, September 9, 2002.
URL: www.pbs.org/pov/afghanistanyear1380/legacy_feature02.php
[5] “The Gorge of Many Sorrows,” Anna Badkhen, Pulitzer Center on Crisis Reporting, March 26, 2011.
URL: pulitzercenter.org/articles/afghanistan-land-mines-marmul-balkh-province
[6] “Country Profile: Afghanistan 2013,” Landmine & Cluster Munition Monitor.
URL: http://the-monitor.org/custom/index.php/region_profiles/print_profile/619

In particular, the design specifications, cost, size, and testing method, were specified in terms of the real-world problem of building a cost effective device in the United States and transporting it to Afghanistan:

- The robot must be autonomous: no human intervention and no tethers.
- The robot must fit in a 12 in. x 12 in. x 12 in. cube for shipping.
- The robot must deploy from its shipping configuration autonomously.
- There is no weight limit.
- Dummy mines will be made of a ferrous material.
- The robot should clear the 7 ft. x 7 ft. test area in less than 1 minute.
- The robot will be allowed three attempts at clearing the test area.
- The total cost of each robot must be under $400.

One significant deviation from the real-world problem bears mention. Real ‘butterfly’ landmines were not appropriate for use in a classroom exercise. Instead, simplistic replicas were cut from

1/8” steel plates. These replicas were made available to students for testing during the course of the project.

As in previous course iterations, project teams were formed by merging lab groups to make formal cooperative learning groups.[1] For the first PBL implementation at Lawrence Tech, ten students were enrolled in the course. Project teams of three or four students each were formed by the instructor. Based on the course early self-assessment survey, project teams were approximately equivalent in self-assessed knowledge of course materials. In addition, students of similar backgrounds were paired. For example, two Brazilian exchange undergraduate students worked together and a Chinese undergraduate student was paired with a Chinese first-semester graduate student. Project teams are shown in Figure 3.

Figure 3. PBL project teams with their autonomous vehicles.

Progress reports were used to keep students on track, gauge progress, and facilitate interaction between teams. Three reports were prepared over the half-semester project and submitted every other week. These reports were presented orally, following a prepared PowerPoint template. The template required a title slide, current progress, and deltas. The title slide included a self-selected project teams name. These team names appeared to help establish a team identity, though no data was taken to confirm this observation. Current progress included accomplishments, distribution of work among team members, and current status of the project. Deltas included changes to process, implementation plan, and missing information. Project teams were free to ask questions of other teams following presentations.

Excerpts from a sample progress report are shown in Figure 4. Student names have been obscured. In this example, students took some liberties with the provided template but also customized the visual appearance to suit their team identity and design.

Figure 4. Excerpted slides from a sample progress report.

Individual accountability for the design process was established in two ways: random presenters of the oral progress reports and peer evaluations. Project teams were made aware that the presenter would be randomly selected before the first progress report due date. After two progress reports, confidential peer evaluations were completed. A portion of the peer evaluation is shown in Table 2. Only one team reported a small problem, which was discussed with the team. After completion of the project, a second confidential peer evaluation was completed by every student. The final peer evaluations indicated no significant problems with distribution of labor or team conflicts.

Table 2. Sample peer evaluation form.

Name	Most Significant Contribution	Strength	Percent Contribution (%)	Other Comments
Your name Responsibility				
Teammate 1 Responsibility				
Teammate 2 Responsibility				
Teammate 3 Responsibility				

The student designs were tested in a friendly competition during the week of final exams. Each team was given three attempts to locate and mark three of the ‘butterfly’ landmine replicas within the playing field. Attempts rotated among the teams and teams were allowed to make modifications to their design between attempts. A simple scoring formula was used, awarding 0.25 points for a robot appearing to locate a mine and 1.00 points for a robot successfully marking the mine. The team with the highest score was declared the winner of the competition, though there was no reward for winning.

Observations and Survey Results

As questions were raised concerning the design project (e.g. What distance must the vehicle maintain from detected landmines? What constitutes marking a landmine?), students were encouraged to answer their own questions while staying within stated problem objectives. For instance, all three project teams independently researched ‘butterfly’ landmines and determined a minimum pressure needed to trigger detonation. By restricting vehicle mass, the teams reasoned that they could drive over mines without detonation, thereby avoiding the need for complicated logic to drive around the landmines while still covering the entire testing field. This decision simplified the software design at the cost of increased complexity in mechanical design.

Responding to a student question about how landmines were to be marked for removal, teams identified that a “mark” need not be physical, so long as the landmine disposal expert easily understood the location. Two teams therefore selected electronic landmine marking systems: one vehicle-mounted LCD display, shown in Figure 5, and one wireless hand-held LCD display. These displays indicated the location of the detected landmines using a Cartesian coordinate system with a predetermined origin. By selecting electronic location marking, the need for physical marking systems, such as ink, powder, magnetics, flags, etc., was eliminated. These teams chose to increase the complexity of the electronic design to simplify the mechanical design.

Figure 5. Onboard LCD display for displaying landmine coordinates.

Following the deployment of the PBL activity, a questionnaire was completed by Lawrence Tech students (N=10) to gauge the effectiveness of the PBL activity. Students were asked to respond to a set of statements regarding the PBL activity and another set of statements regarding the course and instructor. Table 3 shows the results of the questionnaire for all students. As the first iteration of this questionnaire included only 10 students, these results should be considered preliminary. This is a work in progress and these results should not be taken as conclusive.

The questionnaire results were divided among undergraduate (N=4) and graduate students (N=6) and shown in Table 4. Due to the small sample size, these results are provided for qualitative analysis only. There appears to be little difference between responses from undergraduate and graduate students. If confirmed by questionnaire results in future semesters, this would indicate that the benefit from addition of PBL activities in coursework may be extended from undergraduate to graduate courses.

One common response from students was a desire to start the project earlier in the semester. While the authors are concerned about the potential for problems stemming from students engaging in design without the basic tools provided by the lecture and laboratory experiments, there is likely room for compromise. One possibility to be considered is distributing the problem statement early in the course and framing laboratory experiments around expected solutions to the problem. In this way, each experiment would be a part of the PBL implementation.

Another significant question is whether or not the PBL implementation improved student learning in the integrated mechatronic design process. During previous semesters, survey data was not recorded. In addition, direct assessment of student final reports used a generic rubric from the Mechanical Engineering department at Lawrence Tech. A more course-specific rubric for assessing student usage of the integrated design process must be developed.

Table 3. All students' ratings of statements after completion of the PBL activity. Using a scale of 1 to 5, 1 indicates "strongly disagree" and 5 indicates "strongly agree."

	Average	Median	St. dev.
My project accomplished the required task.	4.0	4	0.82
My project employed an innovative design.	4.6	5	0.52
My project was a success.	4.0	4	1.05
I had fun working on the project.	4.7	5	0.48
This project improved my skills in selecting sensors and actuators.	4.7	5	0.48
This project improved my skills in interfacing sensors and actuators.	4.6	5	0.70
This project improved my skills in integrated mechanical-electrical-software design.	4.8	5	0.42
The real-world application of the project motivated me.	4.5	5	0.71
The open-ended nature of the project motivated me.	4.1	4	0.88

Table 4. Undergraduate and graduate students' ratings of statements after completion of the PBL activity. Using a scale of 1 to 5, 1 indicates "strongly disagree" and 5 indicates "strongly agree."

	Undergraduate		Graduate	
	Average	Median	Average	Median
My project accomplished the required task.	4.0	4	4.0	4
My project employed an innovative design.	4.5	5	4.7	5
My project was a success.	4.0	4	4.0	5
I had fun working on the project.	5.0	5	4.5	5
This project improved my skills in selecting sensors and actuators.	4.8	5	4.7	5
This project improved my skills in interfacing sensors and actuators.	4.5	5	4.7	5
This project improved my skills in integrated mechanical-electrical-software design.	5.0	5	4.7	5
The real-world application of the project motivated me.	4.5	5	4.5	5
The open-ended nature of the project motivated me.	4.0	4	4.2	5

Conclusions

This paper detailed the implementation of a half-semester PBL activity in a graduate-level mechatronics course. The MS Mechatronic Systems Engineering program at Lawrence Tech was introduced and the course in question, MSE5183 Mechatronic Systems I, was described. An existing half-semester design project was modified to incorporate elements of PBL. Responses to a post-project questionnaire indicate that students had a favorable view of their learning from the design project. In addition, both undergraduate and graduate students benefited from the inclusion of the real-world problem. In the Spring 2014 semester, the same PBL activity will be introduced at Purdue for further comparisons between undergraduate and graduate students.

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