



Multi-Course Problem-based Learning Module spanning across the Junior and Senior Mechanical Engineering Curriculum: Mechatronics, Fluid Mechanics, and Heat Transfer

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Abstract

A previous teaching grant from the National Fluid Power Association provided senior mechanical engineering students a project to design and fabricate a fluid-powered gantry crane. During fabrication, assembly, and testing of the fluid-powered gantry crane, a number of areas for improvement of the student design were identified. Among these were the inclusion of a control system to limit load swing, redesign of the fluid distribution system, redesign to reduce binding between the trolley and crossbar, and heat sink design for cooling of the electrical system. Rather than fixing the deficiencies with a second senior design project, problem-based learning (PBL) exercises were developed to introduce more students to fluid power using the existing gantry crane. The PBL modules were implemented in junior and senior Mechanical Engineering courses including Mechatronics, Fluid Mechanics, and Heat Transfer. After the PBL activities, direct assessment with a common rubric was used to evaluate the quality of problem solutions and student surveys were used to qualitatively assess the effectiveness of the PBL experience. The assessment results indicate that the PBL activities contributed to student learning both on concepts introduced in class and on problem solving skills which required synthesis of material from class.

Introduction

As part of Lawrence Technological University's (Lawrence Tech) six-year process to incorporate active and collaborative learning (ACL) and problem-based learning (PBL) in the engineering curriculum, courses throughout the A. Leon Linton Department of Mechanical Engineering have been modified to better serve students with ACL and PBL activities.^{1,2} Approximately 75% of the courses in the engineering curriculum are being modified to include ACL and PBL. These courses span the curriculum and range from multidisciplinary Introduction to Engineering^{3,4} to graduate level Mechatronic Systems.⁵ *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 *collaborative learning*. If formal structures exist to guide student interaction, the process is considered *cooperative learning*.^{6,7} PBL, a form of cooperative or collaborative learning, introduces engaging real-world, ill-defined, scaffolded problems for students to solve, usually as part of a group.⁸ Previous work has shown that PBL activities can substantially improve student learning⁹ and that cooperative learning in general promotes academic success, quality of relationships, and self-esteem.¹⁰

This work details the problem-based learning application of a fluid-powered gantry crane, previously designed and fabricated on a small scale by senior mechanical engineering students¹¹, to courses including: Mechatronics, Fluid Mechanics, and Heat Transfer. During fabrication, assembly, and testing of the fluid-powered gantry crane, a number of areas for improvement of the student design were identified. Rather than fixing the deficiencies with a second project, PBL exercises in related disciplines were designed to address the known deficiencies. From a pedagogical perspective, these PBL exercises emphasize the multi-discipline nature of an

engineering design, while allowing a single theme to span multiple semesters. In addition, PBL activities allow the students to learn material that traditional classroom lecture timing does not allow. For example, in fluid mechanics, there is very little time to lecture about the details of pump sizing and selection; a carefully developed PBL exercise will incite the students to do so.

Following PBL implementation, student surveys were used to qualitatively assess the effectiveness of the PBL experience. Rubrics were used to directly assess student performance in course-specific technical domains.

This paper is organized as follows. First, the fluid-powered gantry crane is introduced. In subsequent sections the Mechatronics, Fluid Mechanics, and Heat Transfer PBL problems are introduced. Finally, survey results and assessment of student results are presented and the work is concluded.

Fluid-Powered Gantry Crane

All mechanical engineering students at Lawrence Tech must complete a two semester capstone project. Two options for capstone projects are offered: SAE competition teams and industry-sponsored projects (ISPs). SAE competition teams include Baja SAE, Formula SAE, Formula Hybrid, SAE Aero Design, and SAE Supermileage. The SAE competition projects are well-known by students with prior-years' vehicles available, strict timelines, and a year-to-year process of continual improvement. This makes them attractive to students with aspirations in the transportation industry, but can limit student learning as each student may participate in the design of only a small portion of the vehicle.

ISPs are more varied, representing real, time-sensitive problems posed by industry partners who commit to funding the project. For a typical ISP project, students spend the first semester researching the proposed problem, designing a solution, validating the design using appropriate software tools, and communicating the design to faculty and sponsors. In the second semester, teams fabricate a working prototype, test the prototype, and present the final design with prototype to the industry sponsor. By contrast to the SAE competition teams, ISPs have less strict timelines but no prior designs are made available for reference. This can make the projects very challenging for students, especially in the research phase.

Funded by a teaching grant from the National Fluid Power Association (NFPA), students enrolled in the ISP track were offered the opportunity to design and build a gantry crane that used fluid power for material handling¹¹. The motivation for this work was twofold: to facilitate deep learning about fluid power in a design sequence for the enrolled students and to develop a platform for future classroom and laboratory sessions on fluid power and associated topics. The students developed a pneumatic gantry crane with two degree-of-freedom motion (left-right and up-down) capable of meeting the structural, load capacity, and user interface requirements. The completed gantry crane is shown in Figure 1.

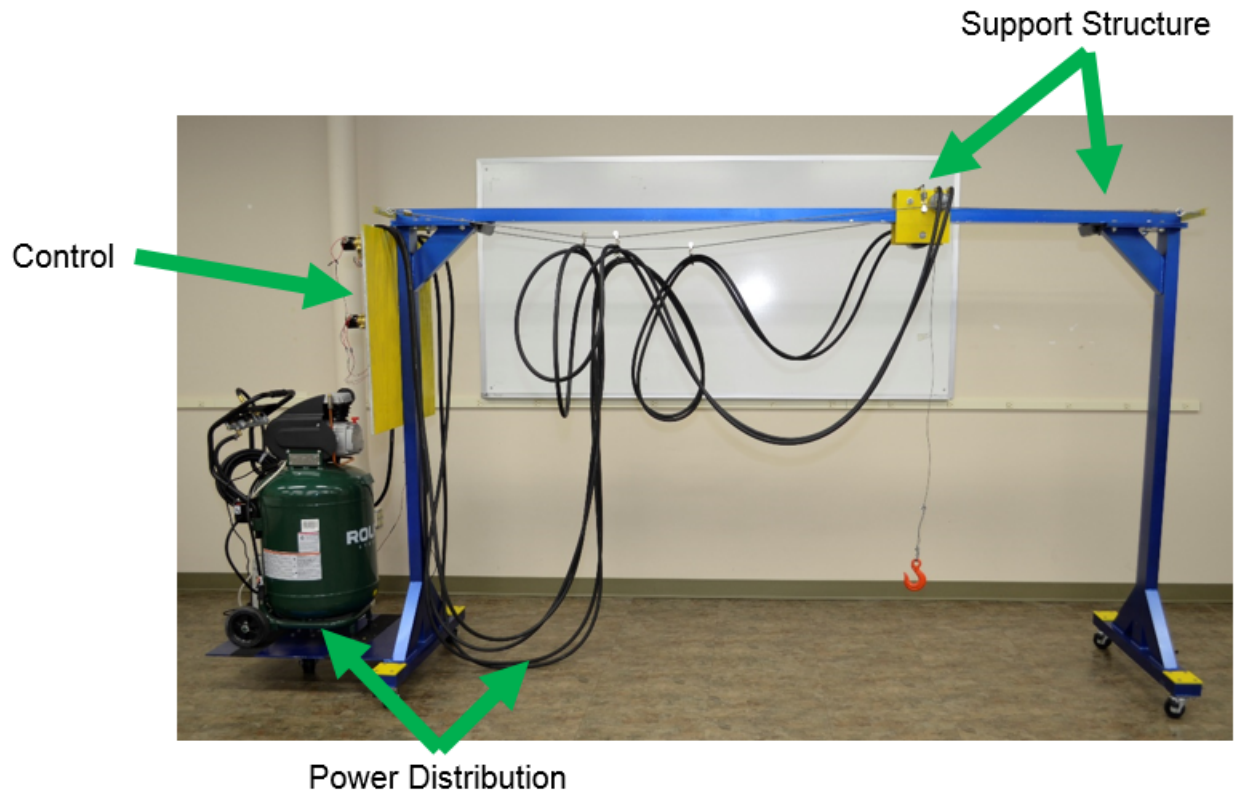


Figure 1. Student-designed fluid-powered gantry crane.

During validation of the student design, several shortcomings were observed by the faculty advisors. Among these were the excessive load oscillation without feedback control, binding between the trolley and crossbar, excessive losses in the fluid distribution system, and little consideration given to electrical power distribution and heat dissipation. These weaknesses were connected to courses in the Mechanical Engineering curriculum as shown in Table 1. Three courses were selected for inclusion of thematically connected PBL exercises to improve student preparedness for future design problems. In the following section, the PBL exercises for Mechatronics, Fluid Mechanics, and Heat Transfer courses are described.

Table 1. Shortcomings observed in student-designed fluid-powered gantry crane and related courses in the Mechanical Engineering curriculum.

Design Flaw	Related Course
Binding between trolley and crossbar	Dynamics, Kinematics
Motor gearing allowed backdriving	Design of Machine Elements
Load oscillation during operation	Mechatronics
Losses in fluid distribution	Fluid Mechanics
Electrical power distribution	Circuits and Electronics, Mechatronics
Electrical heat dissipation	Heat Transfer

Mechatronics PBL Experiences

The first course to be considered is EME 3214 Mechatronics, taught in Fall 2014. While classified as a junior-level course, most students wait to complete the course until their senior year. From anecdotal evidence, this appears to be due to a lack of following courses and student perception that the material is difficult, unrelated to “traditional” mechanical engineering coursework, and unappealing. Ongoing efforts to incorporate ACL and PBL techniques have been made to counter these student misconceptions while bolstering student learning.

Mechatronics is characterized by an integration of mechanical, electronic, control, and computer systems, as shown in Figure 2. Assuming a senior-level mechanical engineering background, mechanical systems include previous coursework in dynamics and fluid mechanics. Electronic systems include previous course work in circuits and electronics. Computer systems include the use of computers in the design phase, as well as new concepts such as A/D, D/A, and microcontrollers. Control systems include entirely new material to introduce feedback control theory and PID controllers. The study of mechatronics is, by nature, interdisciplinary.

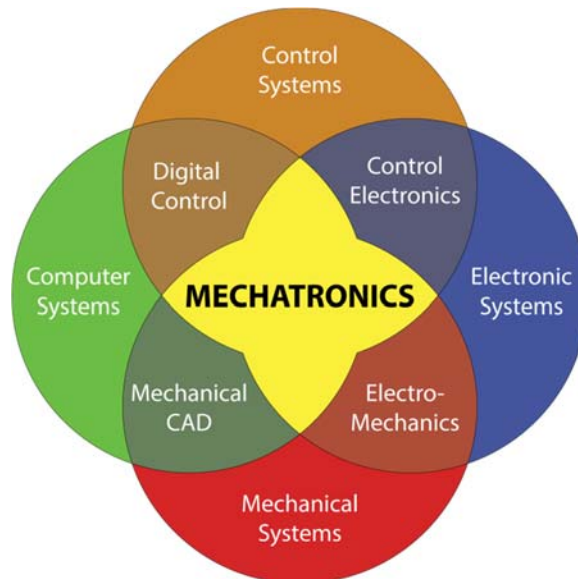


Figure 2. The interdisciplinary nature of Mechatronics.¹²

EME 3214 Mechatronics is taught as a 3 credit lecture with integrated 1 credit lab. Lab sessions are primarily used for the completion of group experiments, but several sessions are dedicated instead to ACL or PBL activities. Course content follows four topics: modeling of dynamic systems, analysis of dynamic systems, integrating mechatronic systems, and feedback control systems. This organization is seen in the color-coded course schedule shown in Figure 3. In Figure 3, modeling of dynamic systems is shown in yellow, analysis of dynamic systems is shown in orange, integration of mechatronic systems is shown in blue, and feedback control systems is shown in green.

Week	Class Period 1	Class Period 2	Videos	Lab Period
1		Introduction	Administration / MATLAB	Fun with Circuits
2	Labor Day	Modeling Systems	Block Diagrams / State Space	Arduino, Transistors, Switches
3	Mechanical Systems	Electrical and Hydraulic Systems	Circuit Analysis, Laplace Transforms	Electromagnet / Paint Sprayer
4	Transfer Functions	Transfer Functions / Stability		Active Filters
5	Case Study: Segway	PBL 1		PBL 1
6	Exam 1	Time Response		PBL 1
7	Time Response	Frequency Response	Fourier Series	System ID (time domain)
8	Frequency Response	Frequency Response	Bode Plots	System ID (time domain)
9	System Identification	Integrating Systems	Diodes / Transistors / OpAmps	System ID (freq domain)
10	Sensor Calibration	Review	Pos. and Vel. Sensors	Sensors 1
11	Exam 2	A/D and D/A		Sensors 2
12	PBL 2	A/D and D/A	DC Motor / Stepper Motor	PBL 2
13	PBL 2	Strain Gages		DC Motor
14	Feedback Control	Feedback Control		Thanksgiving
15	PID Control	PID Control		PBL 3
16	Root Locus Design	Review		PBL 3
	Final Exam			

Figure 3. Color-coded course schedule for EME 3214 Mechatronics.

Three PBL exercises were created to augment lecture and lab material in these four topic areas. The first PBL activity included both modeling and analysis of dynamic systems, the second PBL included integration of mechatronic systems, and the third PBL activity covered feedback control systems. As shown in Figure 3, some in-class time was allocated to PBL exercises 1 and 2 while PBL exercise 3 was accomplished during the final two lab sessions. All three PBL activities were thematically connected for continuity and the same student teams worked together on each exercise. Each PBL exercise included a written report by each student team as well as individual peer evaluations and confidential survey for indirect assessment of student learning. The overall problem assignment is given below.

Wrongful Injury Lawsuit: Who's at Fault?

The M1A2 Abrams tank is an American third-generation main battle tank. The M1A2 weighs in at 68 tons yet manages to reach a top speed of 42 mph while firing the 120 mm cannon reliably, due to a stabilized gun mount.



The Joint Systems Manufacturing Center (JSMC), operated by General Dynamics Land Systems, is a government-owned, contractor-operated facility which makes armored vehicles such as the M1A2. During the fabrication process, workers weld together thick steel plates to form the vehicle hull, turret, and side walls.

The JSMC uses an overhead gantry crane system to move extremely heavy armor sections from the staging area into a work cell and then to move completed turrets, hulls, and sidewalls from the work cells to an assembly area. The crane is operated by a trained worker who uses a handheld pendant to control motion of the load in six axes.



In 2010 a welder was injured when a suspended load knocked over a stack of armor steel. The employee filed a wrongful injury lawsuit claiming that the employer, GDLS, failed to properly train the crane operator. Your team has been retained by the law firm of Stone, McCoy, and Cutter, acting as counsel to the plaintiff, to investigate the incident.

You are tasked with addressing the following questions:

1. Under what circumstances could a suspended load swing beyond the intended pathway?
2. Could any single fault in the crane control systems have caused the injury?
3. Can the faulty crane operation be demonstrated in a courtroom in a dramatic fashion?

Fluid Mechanics PBL Experience

EME 3123 Fluid Mechanics is a junior-level course and two sections were taught in Fall 2014. During the final four weeks of the course, students were tasked to work in a self-selected team of three (with some teams of two) to design the fluid system of a hydraulic gantry crane. Each team was required to submit one technical report describing their detailed design. The project assignment is given below:

Snowmobile “Extraction” System (a.k.a. The gantry crane where failure costs \$1,318,991)

Your rich uncle, Mortimer, has built on his sprawling 20 acres a large storage garage (which is climate-controlled and immaculate) that contains many of his prized possessions: his collection of Porsches, his medieval knights’ armor collection, his gold plated and diamond studded golf club set, etc. Although the garage is very large with a high ceiling, it is packed full of possessions. His snowmobile is the most expensive model available – the 2015 Ski-Doo Renegade X (ROTAX 600 H.O. E-TEC) valued at \$18,991. Its storage spot happens to be in a far corner of the garage behind his 2002 Ferrari Enzo (valued at \$1,300,000). Uncle Mortimer’s estate is in the northern countryside where the winter snow is abundant, so it is not practical to move things out of his garage to access the snowmobile. He has decided that he needs an overhead gantry crane.

Note that Uncle Mortimer is on the Board of Directors for the National Fluid Power Association, so he is requesting that a hydraulic motor is used for the crane (and

that is a very reasonable option for this application anyway). After learning of your vast new knowledge of fluid mechanics, he has asked you to design the fluid system for a gantry crane that can lift and move the snowmobile out of the corner. The crane will need to be able to slide horizontally along an overhead beam and will have a lifting winch.

Some (not all) considerations during the first week of work:

- What is a gantry crane?
- How does a gantry crane work?
- What is a hydraulic motor (as opposed to a pneumatic motor)?
- What components/system does a hydraulic motor (or multiple motors) need to operate?
- There are some subtle yet important design considerations in this project. They are not obvious, so be certain to fully define the problem and constraints before you begin solving the perceived problem. If you have any non-technical questions, your course instructor will serve as your customer (Uncle Mortimer or his wife, Aunt Theodosia, who can answer questions on his behalf). Aunt Theodosia has her own storage garage full of extravagant luxuries.
- Your instructor can assist in some technical questions.
- What hydraulic motors are available that will suit the needs of Uncle Mortimer?

Some considerations after your initial investigations:

- Be cautious that the components and design are not too costly. You should keep track of approximate expenses for components, and keep notes of how you kept costs down. Uncle Mort will want to know. You do not need to consider assembly labor costs.
- You are designing the fluid system only, not the crane structure. You will have to consider the approximate size of the crane parts and where the fluid system will be positioned.
- Be careful with pipe selection (sizing) and material.
- You will need valves, but you do not need to design the valve control system. The Mechatronics students are doing that.
- Do not oversize or undersize your pump.

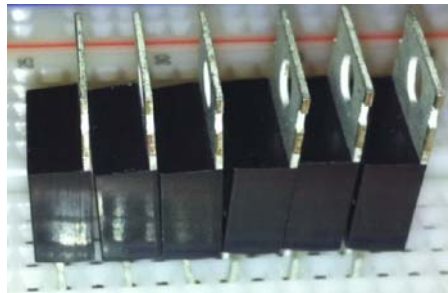
Heat Transfer PBL Experience

EME 4013 Heat Transfer is a senior-level course covering the principles and applications of heat transfer by conduction, convection and thermal radiation. Two sections were taught in Fall 2014. During the final four weeks of the course, a problem-based learning project was assigned and students were tasked to work in a self-selected team of three to address a solution to overheating transistors on a gantry crane. Each team was required to submit one technical report describing their detailed solution. The project assignment is given below:

“HOT” Gantry Crane

(A similar story of rich Uncle Mortimer from EME 3123 Fluid Mechanics was shared: Your rich uncle, Mortimer, installed an overhead gantry crane to move his expensive and precariously placed snowmobile in his large storage garage.)

Once Uncle Mortimer started using his gantry crane, he noticed that the electronics package is poorly designed (i.e., a bunch of transistors are too close to each other, illustratively shown in the figures). The electronics package heats up pretty quickly and causes failure. After learning of your vast new knowledge of heat transfer, he has asked you to design a system that would keep the surface temperature of the electronics at a maximum temperature of 40°C.



Some (not all) considerations during the first week of work:

- What is a gantry crane?
- What is the electronics package used for in the gantry crane set-up?
- What causes the heat generation in the electronics package?
- What are the heat transfer modes in the current system? What is the highest temperature the electronics package can reach?
- There are some subtle yet important design considerations in this project. They are not obvious, so be certain to fully define the problem and constraints before you begin solving the perceived problem. If you have any non-technical questions, your course instructor will serve as your customer (Uncle Mortimer or his wife, Aunt Theodosia, who can answer questions on his behalf). Aunt Theodosia has her own storage garage full of extravagant luxuries.
- Your instructor can assist in some technical questions.

Some considerations after your initial investigations:

- Be cautious that the components and design are not too costly. You should keep track of approximate expenses for components, and keep notes of how you kept costs down. Uncle Mort will want to know. You do not need to consider assembly labor costs.
- You are designing the heat transfer system only, not the gantry crane. You will have to consider the approximate size of the crane parts and where the heat transfer system will be positioned.
- A gantry crane was created by a Lawrence Tech senior project team. I have included some photos for your reference.
- Please note that electronics package is enclosed in a box.

PBL Indirect Assessment

In order to improve the student learning and collect valuable suggestions for future PBL activities, an informal survey was distributed to students to acquire their feedback and feeling about their technical learning. The students were asked whether “This project improved my technical skills in:”, and answers are provided in 5 scales:

1. Strongly disagree
2. Disagree
3. No opinion
4. Agree
5. Strongly agree

Survey questions (Mechatronics Part One: Modeling and Analysis):

This project improved my technical skills in:

1. Making reasonable simplifying assumptions.
2. Modeling dynamic systems.
3. Analyzing the time response of dynamics systems.
4. Analyzing the frequency response of dynamics systems.

Survey questions (Mechatronics Part Two: Sensor and Actuator Integration):

This project improved my technical skills in:

1. Selecting appropriate methods for demonstrating technical results to non-experts.
2. Designing a mechanical support structure.
3. Designing a mechanical motion system.
4. Selecting an appropriate sensor system.
5. Designing an appropriate sensor integration with ADC and signal conditioning.
6. Selecting an appropriate actuator system.
7. Designing an appropriate actuator integration with DAC and amplification.
8. Selecting an appropriate microcontroller.
9. Designing an appropriate microcontroller integration.

Survey questions (Mechatronics Part Three: PID Controller Design):

This project improved my technical skills in:

1. Working with physical mechatronic systems.
2. Modeling dynamic systems using first principles.
3. Modeling dynamic systems using system identification techniques.
4. Selecting desired pole locations from performance specifications.
5. Designing feedback controllers based on desired pole locations.
6. Simulating feedback control systems.
7. Implementing feedback control systems.
8. Using MATLAB and Simulink.

Table 2. Survey results assessing technical skills in Mechatronics.

Question #	Modeling and Analysis		Sensor and Actuator Integration		PID Controller Design	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
1	4.06	0.93	4.00	0.85	3.87	0.83
2	4.00	1.03	3.60	0.83	3.93	0.80
3	3.69	1.35	3.80	0.68	4.13	0.74
4	3.13	1.36	4.00	0.53	4.13	0.52
5	-	-	3.80	0.68	4.07	0.96
6	-	-	4.20	0.41	4.00	0.84
7	-	-	3.60	0.51	3.93	0.59
8	-	-	3.73	0.59	4.20	0.56
9	-	-	3.40	0.74	-	-

Survey questions (Fluid Mechanics):

This project improved my technical skills in:

1. Identifying the components and functions of a hydraulic power system.
2. Making reasonable simplifying assumptions.
3. Analyzing the functions of various flow components (pumps, motors, etc.)
4. Identifying and determining major and minor losses in a flow system.
5. Predicting pressure and pipe size for series piping systems.
6. Determining the required pumping power according to flow requirements.
7. Choosing an actual pump that meets the flow requirements.
8. Designing a real-world fluid mechanics system.
9. Reporting the solution to a customer.

Survey questions (Heat Transfer):

This project improved my technical skills in:

1. Making reasonable simplifying assumptions.
2. Analyzing the causes of heat generation.
3. Identifying and determining the modes of heat transfer (which ones are dominant, which ones are negligible).
4. Determining different and effective methods of heat removal.
5. Reporting the solution to a customer.

Table 3. Survey results assessing technical skills in Fluid Mechanics and Heat Transfer.

Question #	EME 3123 Fluid Mechanics		EME 4013 Heat Transfer	
	Mean	Standard Deviation	Mean	Standard Deviation
1	4.06	0.92	4.09	0.62
2	3.88	0.74	4.24	0.83
3	3.94	0.92	4.00	0.87
4	4.44	0.79	4.47	0.51
5	4.12	0.86	3.94	0.90
6	4.18	0.73	-	-
7	4.12	0.89	-	-
8	3.94	0.94	-	-
9	3.94	0.80	-	-

The data shown in Table 2 and Table 3 implies that the problem-based learning exercises helped students improve their learning on the technical content, and better synthesize information from different topics learned during the semester. Additionally, the results indicate that students were able to expand their knowledge into topics not covered in detail in class. For example, statements 6 and 7 of the Fluid Mechanics survey address pumps. The students' scores of 4.18 and 4.12 are evidence that the students were at least exposed to the topic. Direct assessment can reveal the level of knowledge actually acquired for pumps. Similarly, statements 4 and 6 of the Mechatronics part 2 survey address selection of sensors and actuators. While sensor and actuator calibration and integration were discussed in class, selection was not. The students' scores of 4.00 and 4.20 are evidence that the students were exposed to the topic of sensor and actuator selection.

Written statements were also gathered on the student surveys. The students were asked what they liked (or appreciated) about the project, what should be changed, and any other additional comments/observations. When commenting about what was liked about PBL, two common themes emerged; the students expressed that they liked applying theoretical knowledge from class to a real-world problem, and they appreciated the open-ended nature, "allowing [the students] to explore [their] own designs."

- "There is no exact answer for the question, but you should find one that best fits." (Mechatronics, part 1)
- "Working as a group, work well as a team. Learning more about options for motion control was a rewarding/valuable experience." (Mechatronics, part 2)
- "I liked being able to design and model a system to control the outputs of the system." (Mechatronics, part 2)
- "The project challenged my partner and I to really think about the physical aspects of the equations we were working with." (Fluid Mechanics)
- "The open approach really makes me review what was covered in the class." (Fluid Mechanics)
- "Project created dialogue among students in engineering topics." (Fluid Mechanics)
- "Many different designs could have been used." (Fluid Mechanics)

- “I prefer learning through projects because we are not confined to a ‘box’ in our problem solving like a test. It represents real world engineering.” (Fluid Mechanics)
- “I appreciated the attempt at making the project ‘real world’ and fun. However, a budget restriction would have helped make it even more real world. (Fluid Mechanics)
- “It related to everything we learned in class.” (Heat Transfer)
- “I appreciate the idea and concept behind this project. It gives me a real world problem, gives me a chance to understand problems which are not completely set up/lead for me.” (Heat Transfer)
- “The open-endedness, while frustrating at times, allowed for creativity.” (Heat Transfer)

When asked what should be changed, many students commented that the instructor should cover the material needed to solve the problem or lecture about the material earlier:

- “Find a way to teach project related material earlier in the semester so the project can be assigned and due earlier.”
- “I feel like a bit more directions should be included to narrow down what's needed to be included and what's not, at least budget-wise.”
- “There were many parts of this project that were not included in our design due to them being covered under a different course (pressure vessels, torque on shafts, etc.)”
- “There was very little guidance in what procedure to take, so uncertain of final result. Could be a good thing or not?”

Of course, these are reasons for using PBL. The students should be discoverers of the knowledge they need, they should recognize the multi-discipline nature of the problem, and they should be receiving some of the content “just in time” (as the problem is scaffolded or staged). It is noted that more progress reporting should occur to at least help guide the students better. Following are more students’ comments concerning what they would like changed.

- “I would have liked objective targets such as pricing or packaging. This would make you work harder but let you know you were on the right track when you met the target.” (Heat Transfer)
- “It would be cool to have a cheap project which we could build and prove. Hands on experience is always the most interesting.” (Heat Transfer)
- “Team check up earlier in the project.” (Mechatronics, part 1)
- “Be more clear about the scope of the project. How much detail students should gather about the crane structure, motion of the trolley, etc.” (Mechatronics, part2)
- “Perhaps analyzing a system with given inputs and then redesigning that system through the second phase of the project would be a better way to go. That way we can learn the concepts while we are in school and apply them more effectively when we are actually out in the real world.” (Mechatronics, part 2)

An interesting observation arose when comparing results from the two Fluid Mechanics sections. Section 1 was administered before 5 pm, while section 2 was administered after 5 pm. In addition, the instructor for Section 1 has taught the course for 12 years and employs PBLs in many courses, while the Section 2 instructor has taught the course for only a few years with more limited PBL experience. Results are shown in Table 4.

Table 4. Survey results between two sections of Fluid Mechanics.

Question #	Mean		Percent Difference
	Section 1	Section 2	
1	4.18	3.90	7.0
2	4.09	3.80	7.4
3	4.36	3.70	16.5
4	4.45	4.25	4.7
5	4.09	4.00	2.2
6	4.27	4.00	6.6
7	4.09	3.90	4.8
8	3.91	3.90	0.2
9	3.82	4.10	-7.1

For the most part, the students reported higher gains in Section 1 with the exception of “reporting the solution to a customer.” It is unknown if this is a result of the instructor experience, the timing of the course, or some other factor such as student knowledge-base/motivation.

PBL Direct Assessment

A problem-based learning rubric^{3, 13} shown in the Appendix was used by the course instructors to evaluate the quality of the problem solutions. Note that the students were unaware that the instructors used the rubric nor did its results contribute to their grade. The criteria (i.e., rows within the rubric) have been numbered 1 through 9 with results shown in Table 5.

Table 5. Direct assessment rubric results of PBL.

Criteria	Mechatronics (part 1)	Mechatronics (part 2)	Mechatronics (part 3)	Fluid Mechanics	Heat Transfer
1	3.0	4.0	4.0	3.4	4.0
2	3.5	3.8	4.8	3.7	4.0
3	5.0	4.8	4.0	3.8	4.0
4	3.0	3.5	3.8	3.4	3.5
5	3.3	3.8	3.8	3.8	4.0
6	4.3	3.3	3.3	3.6	3.5
7	3.8	4.0	2.5	3.7	4.0
8	4.5	4.3	4.5	3.8	4.0
9	3.8	3.5	3.5	4.1	4.0
average	3.78	3.86	3.78	3.68	3.89

A comparison of the indirect and direct assessment results is not possible, since the survey reports specific knowledge gained while the rubric reports generalizations. In other words, the survey reports gains in knowledge and the rubric reports how information was presented. Nonetheless, the average score of all nine Fluid Mechanics survey questions is 4.05 and the average score of the nine Fluid Mechanics rubric criteria is 3.68. The difference between the

averages may indicate that the students have more confidence in their abilities than the reports convey. The average scores on Mechatronics (parts 1, 2, and 3) survey questions were 3.72, 3.79, and 4.03 while the average scores on the Mechatronics rubric criteria were 3.78, 3.86, and 3.78. In this case, the difference is less clear. Mechatronics, part 3 may agree with the Fluid Mechanics results in which case the students have more confidence in their abilities than is indicated by their reports.

Conclusions

A student designed fluid-powered gantry crane was used to develop problem based learning modules implemented spanning across the junior and senior Mechanical Engineering courses including Mechatronics, Fluid Mechanics, and Heat Transfer. In conclusion, the use of a multi-course PBL module proved successful at integrating a real-world problem into junior and senior level courses in the BSME curriculum. Indirect assessment results implied that the PBL activities contributed to student learning both on concepts introduced in class and on concepts which required synthesis of material from class. Direct assessment with a common rubric was used to evaluate the quality of problem solutions.

Several areas for improvement were identified. First, additional sections of each course should be tracked to increase sample sizes. Second, to better span the junior and senior level courses in the BSME curriculum, additional courses should be incorporated, especially targeting solid mechanics and machine design topics. Finally, problem-specific improvements were identified. Owing to limited PBL experience, the PBLs deployed in Mechatronics did not provide a sufficiently narrow scope to students, resulting in student frustration due to too many options. This was especially apparent in the second Mechatronics PBL. All PBLs explored would benefit from progress updates to keep students on task.

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Appendix

Problem Based Learning Rubric

Team: _____ Project/Assignment: _____

<i>Criteria</i>	<i>1</i> <i>No Demonstration</i>	<i>2</i> <i>Attempted Demonstration</i>	<i>3</i> <i>Partial Demonstration</i>	<i>4</i> <i>Proficient Demonstration</i>	<i>5</i> <i>Sophisticated Demonstration</i>
Identification of Problem	No attempt to identify a problem	Poses a question for inquiry	Formulates a question with a plan for inquiry that identifies skills, knowledge, people, tools, or other resources associated with the solution	Formulates a question with a plan for inquiry that details the skills, knowledge, people, tools, and other resources needed to answer the question	Formulates a compelling question with a plan for inquiry that details the skills, knowledge, people, tools, and other resources from two or more disciplinary perspectives
Data Collection	No attempt to record data	Records and/or references observations, concepts, or details from primary or secondary sources	Records, interprets, and/or references observations, concepts, and details from primary and secondary sources	Applies standards to properly record, interpret, and reference relevant observations, concepts, and details from primary and secondary sources	Consistently applies high standards to properly record, interpret, and reference relevant observations, concepts, and details from primary and secondary
Representing Data	No attempt to represent data	Data is poorly represented in written or graphic form	Data is represented in written or graphic form using technical terms	Data is represented in written or graphic form using appropriate technical terms appropriate to the field	Data across a variety of disciplines is synthesized in written or graphic form using appropriate technical terms appropriate to the field
Verify and evaluate information	Makes no attempt to evaluate resources or data	Attempts to evaluate some resources but draws no reasonable conclusions	Evaluates some resources and data OR evaluates data and resources but draws incomplete or inaccurate conclusions	Evaluates resources and data accurately, considering credibility of sources, verification of findings, and reasonableness	Evaluates and verifies resources and data by generating original data to compare with others' findings OR by locating additional primary sources
Draw conclusions and make appropriate applications	Makes no attempt to draw conclusions or make appropriate applications	Attempts to draw conclusions from research or data analysis but they are inaccurate or irrelevant to the project	Draws some conclusions that are accurate or relevant to the project and/or uses some of the information appropriately in planning and carrying out activities	Draws accurate conclusions that are relevant to the project from research or data analysis AND uses the information appropriately in planning and carrying out activities	Draws accurate, relevant conclusions from research or data analysis and uses the information to justify and applies them in a sophisticated manner.

Justify and support decisions, strategies, findings and solutions	No explanation or justification of decisions, strategies, findings and/or solutions	Explanation used to justify and explain decisions, strategies, findings and/or solutions is not relevant to the project	Explanation used to justify and explain decisions, strategies, findings and/or solutions is not connected to the information gathered while completing the project OR is incomplete	Explanation used to justify and explain decisions, strategies, findings and/or solutions is complete and is supported by evidence gathered while completing the project	Explanation used to justify and explain decisions, strategies, findings and/or solutions is complete and is supported by evidence gathered while completing the project in a sophisticated manner.
Purpose	No product	Unclear purpose or main idea	Communicates an identifiable purpose and/or main idea for audience	Achieves a clear and distinct purpose for a targeted audience and communicates main ideas with effectively used techniques to introduce and represent ideas and insights	Achieves a clear and distinct purpose for a targeted audience and communicates main ideas with a variety of techniques to introduce and represent ideas and insights
Organization	No product	Organization is unclear; introduction, body, and/or conclusion are underdeveloped, missing, or confusing	Organization is occasionally unclear; introduction, body, and/or conclusion are underdeveloped,	Organization is clear and easy to follow; introduction, body, and/or conclusion are defined and aligned with purpose	A clear organizational structure enhances audience understanding; introduction, body, and conclusion are well defined, effective, and aligned with purpose
Detail	No Product	Supporting details and/or visuals are missing, irrelevant, inaccurate, or inappropriate	Supporting details and/or visuals are relevant but limited, overly general, or inconsistently provided	Relevant use of supporting details e.g. analogies, comparisons, examples, descriptions, AND/OR visuals e.g. symbols, diagrams, graphs, tables, maps, models	Uses a variety of clear, pleasing, and relevant supporting details that contribute to the audience's understanding