

# Integrating Theory and Hands-On Practice using Underwater Robotics in a Multidisciplinary Introductory Engineering Course

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## Abstract

This Complete Evidence-based Practice paper will focus on the design, implementation, and evaluation of a multidisciplinary introductory engineering course that integrates theory and hands-on practice around a theme of underwater robotics. The course is required for all students (including non-engineering majors) at a small liberal arts college and is the first engineering course for the majority of enrollees. The previous version of the course was a traditional lecture-based introduction to lumped element modeling of mechanical and electrical systems and modeling of signals using a Fourier analysis approach. The new version of the course covers most of the same technical content, although a Laplace transform approach has replaced the Fourier transform approach and a brief introduction to control theory has been added.

Based on best practices in engineering education, the course design and implementation team has moved from the lecture model to a model that includes active learning (flipped classroom) tutorials and hands-on practicums. Students watch videos created by the instructors before the first tutorial session of the week, then come to tutorial to take both individual and team quizzes (similar to Team-Based Learning practices) and work with their teams on a short problem that provides real-world context for the content covered in the videos. The second tutorial session of the week is dedicated to context-rich problem solving with significant interaction between the instructors and students. Following the two tutorial sessions each week, students take part in a 2.5-hour practicum session where they experience the content in a hands-on environment, with most practicums focused on an aspect of the underwater robot. For example, the robot is placed in a water tank with a buoyancy "spring" attached and a chirp signal is input to the thruster to obtain a Bode plot response of the robot's position versus thruster input frequency.

Evaluation measures include a pre/post attitudinal survey regarding the usefulness of class content, intent to major in engineering, and understanding of the engineering profession and pre/post content tests from both the previous, lecture-based incarnation of the course, and the new version of the course. Results show significant increases in student learning, affective gains, perceived understanding of the field of engineering, and an erasure of a previous gender gap in course performance.

# Introduction

An ideal introductory engineering course would expose students to the rigor and excitement of engineering through the design, modeling, and analysis of engineering systems. Because first year students often lack the technical background to take on detailed modeling and analysis, successful introductory courses situated in the first year of the curriculum are often focused on conceptual design. The core curriculum of Harvey Mudd College (HMC), an undergraduate institution offering STEM majors only, includes a course entitled Introduction to Engineering Systems; this course is required for students of all majors, and is typically taken in the Fall semester of the sophomore year. A separate course in engineering design, required for majors

only, can be taken previously or concurrently with the Engineering Systems course. This curricular flow opens up the ability to lean on technical knowledge accumulated in introductory physics and mathematics courses to immerse students in rigorous mathematical modeling and analysis.

# Existing Introductory Course and Review

For a little over ten years, this Introduction to Engineering Systems course focused on engineering signals and systems, covering signal representation using Fourier series, sampling, lumped element modeling of linear time-invariant (LTI) mechanical and electrical systems, and step and frequency response of LTI systems. The course was taught to approximately 200 students annually in a standard lecture and recitation format, with two 75-minute lecture periods followed by one 50-minute recitation period each week.

In the Fall of 2014, the Harvey Mudd College Engineering Department embarked on a review of the Introduction to Engineering Systems course, motivated by a general need for periodic review, but also by a broad concern across engineering faculty that the course was not as effective as it could be and the perception that both students and faculty from other departments on campus under-valued the course. Feedback was collected from a number of stakeholders, including:

- Engineering faculty focus groups (total of 19 participants, which covered all full-time tenure-track faculty)
- Surveys and discussion with other departments (5 departments)
- Feedback from the Engineering Visitors Committee (an advisory committee composed of distinguished engineers and educators)
- Senior student focus groups (4 groups, 16 students in total)
- An alumni survey (246 responses, a 42% response rate for four graduating classes spanning nine years)

Additionally, the Student Evaluations of Teaching (SET) data were compiled for the previous eight semesters and compared with SET results for other engineering courses over the same time period.

Briefly, analysis of these data all led to the following conclusion: the existing course did not give students a sense of what most engineers do, nor did it expose them to the experiential learning that is fundamental to engineering. Furthermore, students did not feel that they learned as much in the existing course as in most HMC classes. This showed up in the focus groups, alumni surveys, and SET data: for example, over eight semesters, the Introduction to Engineering Systems course received an average SET score of 4.75 on a 7-point Likert scale for "I learned a lot in this course". The average score on this same item for all other engineering courses was 6.02 out of 7; the difference is statistically significant, with p < 0.001.

## **Desired Outcomes for Course Redesign**

In addition to feedback on the existing course, the feedback mechanisms above were also used to inform the design process for a potential course revision. Objectives and constraints were identified to assist in the generation and evaluation of course redesign alternatives; the full set of objectives and constraints are shown below in Table 1, but these can largely be grouped into five general desired outcomes as follows:

For a diverse student body, including both engineering majors and non-engineering majors and students from underrepresented groups,

- 1. Increase engagement in a rigorous engineering course.
- 2. Increase utility of a rigorous engineering course.
- 3. Increase student learning in a rigorous engineering course
- **4.** Increase student understanding of the engineering field and major.
- 5. Maintain (or decrease) student workload.

 Table 1: Objectives and constraints used to assist in conceptual design and evaluation of course redesign alternatives.

Course Redesign Objectives (listed in approximate order of decreasing priority)	Course Redesign Constraints
Maximize utility for all students (majors and	Maintain essential content for majors in
non-majors)	current engineering curriculum
Maximize student engagement	Maintain a 3-credit course with
	commensurate workload
Maximize student understanding of	
engineering field and major	
Maximize (maintenance of) rigor	
Maximize (maintenance of) depth	
Maximize number of engineering faculty who	
can teach the course	
Minimize resources	

Four course redesign alternatives were evaluated, including a design-build-test course, a conceptual design course, a problem-based learning format (based on existing content), or an experiential learning course format (based on existing content). These designs were all informed by and evaluated based on the theoretical framework discussed in the following section, but for the sake of brevity further discussion in this paper will focus on the selected course design: paired classroom and experiential learning, in which classroom learning is connected each week to hands-on experience in a practicum.

## **Theoretical Motivation**

The theoretical motivation underpinning the course redesign was a coupling of Kolb's Experiential Learning Theory and a suite of evidence-based pedagogy. Kolb's Experiential Learning Theory (ELT) posits that learning results from a cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation (see Figure 1) [1,2]. A course that repeatedly moves students through this cycle should therefore result in high levels of student learning. Such cycling was implemented in our redesigned course by the overall course structure, in which students were introduced to new material first by recalling previous concrete experiences, reflecting on these experiences, interacting with engineering theory related to those





experiences, and then experimenting with that theory in the hands-on practicum. The practicum itself also created another set of concrete experiences, which was used as a basis for another round through the cycle, often via homework problems related to the practicum (see next section for details).

To design the activities aimed at moving students through the ELT cycle, we integrated a suite of research-proven pedagogical methods; these methods included modes of active learning, collaborative learning, and frequent low-stakes testing. That active learning is superior to traditional lecture has been proven unequivocally: Freeman et al.'s meta-analysis of 225 studies showed that active learning increases student performance on examinations and concept inventories by 0.47 SDs, and students taught using traditional lecturing are 1.5 times more likely to fail than those taught using active learning [3]. As detailed in the next section, the redesigned course implemented many aspects of team-based learning (TBL), a collaborative, problem-based learning method. TBL divides course material into modules, and students learn the material in each module by preparing (e.g. reading or watching videos), undergoing individual and team in-class testing, then moving on to application-focused exercises carried out in teams [4]. TBL has been proven to increase learning, particularly for lower-performing students [5,6]. Additionally, frequent testing has been shown to improve student learning [7], so the individual and team testing occurred each week in our redesigned course (see details below). Finally, a highly structured course design including active learning with high engagement levels and frequent low- or no-stakes testing has been shown to raise the performance of all students, with disproportionate benefits for underrepresented minorities [8].

## **Detailed Course Design**

The revised course had to be carefully designed to effectively integrate the aforementioned educational practices suggested by theory. Because in-class time was limited, a flipped classroom format was used in which content was delivered via instructor-made videos which students watched outside class meeting times. The flipped classroom format has previously

been proven to be equally effective as other active learning methods [9], and allowed for the use of class time for active, team-based and hands-on learning without sacrificing content. Additionally, the flipped classroom format allowed students to meet in many small (30-35 student) sections staffed by multiple instructors (two professors and one undergraduate assistant) instead of meeting simultaneously in a large lecture hall. The following section describes the active learning techniques that were used, considerations for the design of individual problems used in active learning activities, the weekly schedule necessary to accommodate these activities in many small sections, and considerations for the design of the semester-long schedule.

## Active Learning Techniques and Assignment Design

Students interacted with course content in five ways in the redesigned course: videos, quiz tutorials, problem tutorials, practicums and homework. Content for the course was delivered in the form of a series of videos which the students were assigned to watch before the first class of each week. These videos were kept brief (5-20 minutes) in keeping with best practices of video design [10]. Each video featured (no-stakes) quiz questions that allowed students to test their understanding of the material.

In keeping with TBL practices and the desire for frequent low-stakes testing, class time in the first class meeting of each week was dedicated to testing students on the content of the videos. Students were asked to individually take a short quiz. The questions on these quizzes were focused on recall and very simple application because students had not yet practiced related problems or asked instructors questions. After taking the quiz individually students would retake the quiz in a group of six using scratch (IF-AT) cards that allowed them to make multiple attempts on each question. Instructors took questions on the subject material after the quizzes and clarified any common misconceptions that the individual quiz answers had revealed. These activities combined to take thirty to forty minutes of the first fifty-minute class, the balance of the meeting was spent on a practice problem to shore up understanding of the material. Class meetings that were carried out in this style were referred to as quiz tutorials.

The second class meeting each week had two goals: to cement concepts by providing students practice using them, and to provide context to seat the abstract mathematical and engineering concepts in the real world. As a result, the meetings – referred to as problem tutorials – featured students working on context-rich problems while interacting frequently with instructors. The major challenge of these meetings was designing the problems: both engagement with the material and the communication of context hinged on problems that were interesting, practical, and clearly connected to the world. This challenge was addressed by deliberately selecting examples from a wide variety of engineering, physics, chemistry and biology disciplines. For example, students analyzed a control system of a self-driving car, viscoelasticity of skin, and dynamics of large structures like dams in addition to the more traditional vehicle suspensions and RLC circuits. An example problem appears in Appendix A.

The final class meeting of the week was a hands-on activity related to an underwater robot. This section was longer than the tutorials (2.5 hours instead of 50 minutes) and had more instructor support (one professor and one undergraduate assistant per 16 students). The goal was to apply the theoretical techniques developed in the week's tutorials in a real engineering setting to a real engineering system and move students through the ELT cycle. The connections between the tutorial module topics and practicums are depicted below in Figure 2.



Figure 2: Connections between tutorial module content and corresponding practicums.

The practicum also exposed students to practical aspects of engineering like using tools to build mechanical systems and benchtop electronics to measure electrical systems. Because the students were relatively inexperienced in the practical techniques required, they were not evaluated on the outcome of practicums but rather on the effort they put into mastering the skills and carefully carrying out the experiments. This was meant to reduce student stress and allow students to focus on the conceptual learning in the practicums. Where possible, the practicum was simplified so that students could interact directly with class concepts. For example, the force measurement practicum in Appendix B asked students to interact with a force measurement apparatus that was already constructed so that they could take measurements without learning about the machine's internals.

Homework was another opportunity for students to practice using the material taught in tutorials and another opportunity for well-designed questions to place the techniques students were learning in the larger engineering context. The practicum was a particularly rich source of context for the problems tackled during weekly homework assignments and in-class tutorial sessions. Notably, each homework included one problem that was based on data collected during the previous week's practicum, or one problem that required calculations/derivations necessary to complete the following week's practicum. In addition, theoretical material necessary for a practicum was often taught in the problem tutorial immediately preceding it. Again, this aided in the movement of students through the ELT cycle.

For example, the practicum in Appendix B guides students through measuring forces on their robots to make a dynamic model of the underwater robot they had just assembled. The details of the dynamic model were discussed in the preceding tutorial. Underwater robotics is a multi-disciplinary field, which made it easier to design this sort of parallel instruction in tutorial and practicum.

# Weekly and Semester Schedule Considerations

This type of instruction created natural dependencies between students learning material in videos, cementing it in tutorial and deploying it in practicums. The weekly schedule of the course had to be carefully designed to meet those dependencies and to distribute student deadlines so that they could dedicate appropriate focus to each part of the class. This was accomplished using the weekly schedule depicted in Table 2 and discussed below. In addition, practicum concepts had to be carefully aligned with tutorial concepts as shown in Figure 2.

 Table 2: Weekly schedule for the course.

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
		Quiz Tutorial				
		for Week N		Problem Tutorial for Week N and	Practicum Slots	Practicum Slots
AM		Material		Homework Due for Week N-1	for Week N	for Week N
	Finish Video					
	Set for			Practicum Slots for Week N and	Practicum Slots	Practicum Slots
PM	Week N			Videos Posted for Week N+1	for Week N	for Week N

# Helical Course Design

In the same way that a large-scale engineering project builds over time and is comprised of multiple parts that are interrelated, the new course was designed such that topics and practicums built on each other to end in a culminating experience. For example, in the first practicum, students were asked to construct an underwater robot. The practicums that followed required students to build the mechanical models, simulations, electronics, control theory, and sensor package of the robot. The final practicum then required students to bring their completed robot to a nearby lake, deploy the robot at a desired GPS location, have it autonomously track a desired depth, and collect temperature measurements at that depth. This was a helical ELT cycle, built on weekly cycling.

# Changes to Course Content

In addition to the pedagogical changes made when revising the course, some changes were made to the course content. The key content changes were the additional of feedback control, the significantly reduced focus on signal representation, and the use of Laplace transforms in place of Fourier transforms. The full set of learning outcomes for the original and revised course, as well as the modules in each version, are available in Appendix D.

# **Evaluation Methods**

The evaluation methods used to measure outcomes are summarized in Table 3 below. Each method was used in the Fall 2015 implementation of the original course and then repeated with the redesigned course in Fall 2016. Instructor effects on performance and attitudes should be minimal, as six out of the seven instructors for the course were the same for both offerings.

Evaluation Outcome	Method
Increase engagement in a rigorous	Pre/post survey
engineering course.	Student Evaluations of Teaching (SET)
Increase utility of a rigorous engineering.	Pre/post survey SET
Increase student learning in a rigorous engineering course	Pre/post test Final grades (for gender comparison only) SET
Increase student understanding of the engineering field and major.	Pre/post survey
Maintain (or decrease) student workload.	SET

The survey results included quantitative and qualitative responses; quantitative measures were analyzed in aggregate and as paired pre/post tests for those students who responded to both surveys. Qualitative responses were examined for themes by Dr. Laura Palucki Blake, a trained social scientist who was not a course instructor, to reduce bias. The pre/post test consisted of two long-answer problems, one focused on the frequency response of a mechanical system and the other on the transient response of an electrical system.

Additionally, reflective feedback from instructors was collected after the end of the Fall 2016 semester and instructor contact hours were counted and compared to those in other courses.

# Results

The evaluation methods described above were used to assess the five desired course outcomes. Data supporting achievement of each outcome is referenced and discussed below.

# 1. Increase engagement in a rigorous engineering course

As one means to assess engagement, students were asked during pre- and post-course surveys whether they were "excited about this course" for both the original course offering (dark blue) and the revised course offering (green). The first column set in Figure 3 illustrates the improvement in course excitement between courses. Not only did students begin the new course with a more positive attitude (3.7/5.0 with the new course vs. 3.1/5.0 with the previous course; the increase is likely due to positive word of mouth surrounding the course redesign), but the level of excitement slightly increased with the new course and decreased with the previous course. Specifically, matched pair (pre/post) data showed that the previous course decreased excitement levels (3.1/5.0 to 2.9/5.0, p<0.06) while the new course increased excitement levels (3.7/5.0 to 3.9/5.0, p<0.05).

When the new course's data is dissected to observe differences in "excitement about the course" between engineering majors and non-engineering majors, it can be seen that for engineering majors there is a significant increase in course excitement between the time the new course started and ended. Specifically, excitement increased from

4.1/5.0 to 4.5/5.0 with p < 0.05. More interesting is that for non-engineering majors, there is still a significant increase in student excitement about the course, i.e. from 3.3/5.0 to 3.7/5.0 with p < 0.05. Furthermore, while male students in the new course did not report a significant increase in excitement about the course (3.8/5.0 to 3.9/5.0), female students did report a statistically significant increase, i.e. from 3.5 to 3.9 with p < 0.01.

Another increase related to engagement also appears in SET results, where the average response on a 7-point Likert scale to "This course stimulated my interest in the subject matter." increased from 4.1/7.0 for the original course to 5.9/7.0 for the redesigned course.

## 2. Increase utility of a rigorous engineering course

A direct measure course utility is extremely difficult, as the skills students will use in their future careers cannot be predicted. However, we were able to measure perceived utility using the pre/post course survey question "How valuable is the course to your overall education?". As shown in the second column set of Figure 2, there was an increase in the students' perceived value between the two courses from 3.7/5.0 to 4.3/5.0. As well, there was an increase in the student's expectation of whether their "career will utilize" what is learned in the course from 3.2/5.0 (old course) to 3.6/5.0 (new course).

Furthermore, one post-course survey qualitative response theme was that students, regardless of major or intended major, clearly articulated the value of what they learned in the redesigned course. In addition to specific skills like Laplace transforms and Bode plots, they also mentioned overarching larger goals of modeling systems and solving problems that are hallmarks of systems thinking.

"It seemed like the concepts presented were very fundamental and general--i.e. not limited to a specific engineering field, or even engineering at all in some senses. I think this class will be a useful jumping off point for the rest of the engineering curriculum."

"I think it lays foundation on the way I see real-world problems. Even though I am not an engineering major, I think many concepts can be modified and adapted to solve problems in other fields."

## 3. Increase student learning in a rigorous engineering course

Student learning, possibly the most important metric, was first assessed through pre/post test. As shown by Figure 4(a), there was a statistically significant increase in post course problem set scores when comparing how students scored after taking the previous course versus the new course. In Figure 4(a), there are two sets of scores, one that shows the mean of all student scores, along with a second that shows the mean scores after zero scores were removed from the data set (to eliminate the influence of

students who did not attempt to answer the questions.) Even this reduced set of data shows a relatively large improvement in learning, from 6.1/10 to 8.0/10, p < 0.001.

Student perception of learning also tracked with the measured increases in learning, as evidenced in the increase in SET responses to "I learned a lot in this class.", which increased from 5.0/7.0 to 5.9/7.0.

The original course offering had, over several years, resulted in a statistically significant difference in final grade performance for males vs. females, with females receiving lower grades than males. Although the differences in performance by gender in the last two offerings of the original course were not statistically significant, males were still outperforming females, on average. In the revised course offering, this difference has disappeared: as shown in Figure 4(b), there is no significant difference between the final grades of male and female students, (male mean 84.2%, SD 9.5%; female mean 84.9%, SD 7.2%). Future analysis will examine post-test performance by gender.

#### 4. Increase student understanding of the engineering field and major.

The third survey item results shown in Figure 3 illustrate how students perceive their understanding of the field of engineering. While both the previous and new course versions had roughly the same perception of having a "Solid understanding of what it means to be an engineer", i.e. 2.9/5.0, students in the new course increased their perceived understanding to 3.6/5.0, while students in the previous course only increased their perceived understanding to 3.1/5.0.

These increases in perceived understanding of the engineering field achieved by the new course can be broken down into increases accomplished by engineering majors (from 3.3/5.0 to 3.7/5.0, p<0.01) and by non-engineering majors who saw a larger increase in perceived understanding (from 2.8/5.0 to 3.6/5.0 with a p<0.001). Surprisingly, the increase was statistically significant (p < 0.001) for both male and female students, but the pre/post increase for male students in the revised course was 10% higher than that of female students (males went from 2.9/5.0 to 3.9/5.0; females from 2.9/5.0 to 3.4/5.0).

#### 5. Maintain (or decrease) student workload.

One of the more difficult goals to measure is maintenance of student workload. Unfortunately, the only available data relating to workload are responses to a SET question asking students to self-report the number of hours they typically spend on the course per week. Although self-report is notoriously unreliable, we do feel that comparing the reported hours for the original course and those reported for redesigned course can at least indicate the perceived workload. The original course had 3.4 lecture/recitation contact hours plus a reported mean of 8.1 out of class work hours, while the new course had 4 class/practicum contact hours plus a reported mean of 5.9 out of class work hours (see Figure 5). Hence the total workload, as reported by students, decreased from 11.5 hours to 10 hours per week.



**Figure 3**: Pre/post survey results for the original and redesigned course (*N* = 205, 94 for original course pre, post respectively; *N* = 121, 201 for revised course pre, post respectively).



**Figure 4:** Student post-test results are shown in (a). Scores were out of 10, and the mean and standard deviation are shown for cases with (N = 118 for original course and N = 182 for revised course) and with all zero scores removed from the samples (N = 97 for original course and N = 179 for revised course). In (b), the final grades of students in new course (out of 100%), differentiated by gender.



**Figure 5:** Student Evaluation of Teaching (SET) results for the original course (dark blue, left of each pair) and revised course (green, right of each pair). All items except "Average hours per week spent outside class meeting time" were evaluated using a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). Six out of the seven course instructors were identical across these two offerings.

# Instructor Reflection Results

Three main themes emerged from the instructor reflections on the course redesign: the high quality of interactions with students, student enthusiasm for course and course material, and the high number of contact hours in the redesigned course. Clearly the first two were beneficial, while the third is a concerning element of the course design.

## Conclusions

Kolb's Experiential Learning Theory and a number of research-based pedagogical methods were used to redesign HMC's Introduction to Engineering Systems course. The new course featured flipped, active-learning tutorials with elements of TBL and context-rich problems, paired with hands-on practicums designed to show physical manifestations of theory learned in the classroom and move students through the ELT cycle. As compared to the original, lecture-based course, the redesigned course showed statistically significant gains in student learning, as well as affective gains for both majors and non-majors. Moreover, the revised course design significantly increased enthusiasm for the material amongst female students, and removed the gender gap in final grade performance seen in the original lecture-based course. It is also worth noting that while instructors often shy away from a shift from traditional lecture to active learning due to concerns about decreases in SET scores, our results show either increased or maintained SET scores across all evaluation measures (excepting workload).

The most significant drawback to the redesigned course is the increased instructor workload. Creation of new video lectures, context-rich tutorial and homework problems, and practicum experiments is time consuming for instructors, although such tasks are generally only required during course development. More relevant on an ongoing basis, while the increase in weekly contact hours and low student-to-faculty ratio may have benefitted student learning, it also required significant additional instructor contact time. In response to this issue, future offerings will restructure the class tutorial and practicum instructor-to-student ratios with the hope of reducing individual instructor contact hours while maintaining student performance.

Based on this experience, we suggest that those seeking to make a similar change spend significant time gathering data on the current offering, and significant time in the course design process. This commitment of time allowed for both the collection of baseline data, time for overall course design followed by more detailed, research-informed design before implementation, and increased buy-in from the department and the college as a whole. Additionally, the instructors involved in the design and teaching of this course each received a one-course reduction in teaching load over the academic year in which this was implemented; this reduction allowed the instructors to focus on polishing the course while it was ongoing. Finally, for those specifically interested in adding a practicum-type experience, we recommend that significant effort be made in providing students with practicums that provide a different method of learning the same theory taught in classroom, as opposed to using the time in practicum to learn new topics.

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### **Appendix A**

Tutorial problems were designed to give students practice with fundamental concepts and motivate learning with real world context. The following example was used for practice with frequency response in Module 4.

#### **Context provided in class**

The viscoelastic nature of skin was introduced with a variety of motivating examples as shown in Figure A1. In an earlier tutorial (in Module 1) different models of viscoelasticity (Figure A2) had been presented. The tutorial problem involved an experiment using an indenter, explained using the images in Figure W3.



3D printed skin psfk.com



Haptic interface wired.com



Study for animating skin dynamics gl.ict.usc.edu











**Figure A3** (a) Indenter system from Boyer et al.<sup>2</sup> (b) Lumped element model of skin loaded by indenter.

#### Problem statement given to students

Students were provided with the following problem statement:

Skin mechanical properties can be measured *in* vivo<sup>1</sup> using dynamic indentation, in which an indenter of known mass sits on top of the skin and receives a sinusoidal force input. The position of the indenter is tracked and, by testing a variety of frequency inputs, a Bode plot of the skin's response can be generated. Boyer et al.<sup>2</sup> used this method to measure response of skin for three different age groups: "young" (dashed line), "intermediate" (solid line), and "old" (dotted line) using an indenter of mass = 4.2 g. Assuming that skin can be modeled using a Kelvin-Voight model (spring and damper in parallel; negligible mass), use the Bode plots below to estimate the spring constant and damping coefficient for each age group.



<sup>1</sup> In vivo = on a live subject, as opposed to using excised skin for testing.

<sup>2</sup> Boyer et al., "Dynamic indentation on human skin *in vivo*: ageing effects." *Skin. Res. Tech.* **15** (2009)

## Appendix **B**

# Introduction to Engineering Systems Fall 2016

# Practicum 1C: Experimental Modeling

### 1 Goals

The goal of this practicum is to determine parameters for the mathematical model of the ROV's vertical motion that you developed in week 2. This will require you to measure the mass and buoyancy of your robot. In addition, you will determine the thrust curve for your ROV motor. This curve will be a plot of motor thrust output as a function of motor control input. Together, these measurements finalize your model of the ROV's vertical motion.

## 2 Deliverables

By the end of this practicum session, you and your partner will deliver:

- 1. The force measurement stand's calibration curve relating force to voltage.
- 2. The mass of your robot.
- 3. The buoyancy of your robot.
- 4. The thrust curve of your thruster.
- 5. A plot of the vertical velocity of the ROV from a simulation involving a step change in thrust control. (Section 6.3)

## 3 Parts List

Tools Per Station	Software	Materials/Parts
Laptop Computer (1 unit) myDAQ (1 unit) FC2231 10lbs load cell (1 unit) Force Measurement Stand (1 unit)	P1C.vi Digital – SW - Timed Output.vi	ROV frame (1 unit) Assembled Thruster (1 unit)
Power supply (1 unit) Motor controller board (1 unit) E79 electronics box (1 unit) C clamps (2 units) Assorted masses (~500-2000g)	in HWIOMyDAQ - Rev 1.llb sampleVoltages.xls	

Table 1: Parts for practicum 1C

#### 4 Model Parameter Measurement

#### 4.1 Force Measurement Stand (FMS) Introduction

The parameters we seek to measure in this practicum include the ROV's mass, buoyancy force, and thrust force. Sensors called load cells, such as the one shown below in Fig. 1, convert such forces to voltage. We will be using the FC2231 10lb load cell connected to a MyDAQ to measure the forces we are interested in.

There is one complication to using the load cells to measure the buoyancy response of a submerged ROV: load cells are not waterproof. We will use a device called a force measurement stand (FMS) to translate the forces we're interested in into forces applied to a load cell. A picture of the FMS appears in Figure 2a; a diagram of the FMS appears in Fig. 2b and the dimensions are provided in Table 2.

As shown in Fig. 2b, the FMS has a top beam that rotates about the pivot rod and presses on the load cell. For example, when a weight is hung from the top hook, it will force the top beam to rotate clockwise (CW) about the pivot rod and apply additional force on the load cell.



It is important to note that when no ROV or additional weights are added to the FMS, there is enough initial weight on the top beam to produce a CW torque about the pivot rod. This produces a downward force  $F_0$  on the load cell. Adding weight to the FMS will cause a change in force (relative to  $F_0$ ) felt by the load cell. Throughout the course of this practicum, you will measure the *change in force*.

Notice that a motor is mounted on the bottom of the FMS at your station. We will extract the thrust force for the motor attached to the load cell and assume that it is sufficiently close to thrust force of the motor you made in practicum 1A.

Table 2: Force measurement stand dimensions

Dimension	Length (m)
$r_{\sf load \ cell}$	0.38
r <sub>top hook</sub>	0.61
<b>r</b> bottom hook	0.61
<i>r</i> <sub>thruster</sub>	1.14



Figure 2a: Force measurement stand picture.

#### 4.2 ROV Preparation

To accurately determine the ROV parameters, the ROV must be prepared so that it resembles the configuration that will be used for future experiments.

- 1. Attach an E79 electronics box to your frame. The electronics box can be found in the robot parts box at your lab station along with a Velcro strip which is used for attaching the box to your robot frame. See Fig. 3.
- 2. Attach the vertical thrust motor you built in practicum 1A. See Fig. 3c.
- 3. Show your instructor or proctor that your ROV is ready for the test tank. They will let you know your time slot for taking measurements in the tank room.

**IMPORTANT NOTE:** If your time slot for the test tank room is not immediate, continue on to section 4.3. Otherwise, if your time slot is now, jump to section 4.4 now and come back to Section 4.3 later.



Figure 2a: Force measurement stand dimensions.





(b)

**Figure 3:** Preparing the ROV for parameter measurements. In (a) and (b), images of the ROV before and after attaching the electronics box with the Velcro are shown. In (c) the vertical thruster is attached.

#### 4.3 Plotting and Line Fitting

In this section, you will plot a set of points in Excel and fit a line to the data. That is, you will determine a linear equation that relates force F in N to voltage V in V, e.g.

$$F = c_1 V + c_2$$

where  $c_1$  and  $c_2$  are the constants you will determine.

If you **HAVE** already been to the test tank room to collect measurements: Your data set for this section will be the measurements you collected.

### If you **HAVE NOT** been to the test tank room yet:

Your data set for this section will be a fabricated data set. Download the file named SampleVoltages.xlsx for your data set. You will use the sample data in this file to learn how to plot and fit the data, then repeat with your measured data set later.

- 1. Your data set should include a list of (voltage, mass) pairs, where the voltage was measured by the load cell for each different mass hung from the top hook of the FMS (see Fig. 1). This data will be used to create a calibration curve relating voltage to applied force. There are a few points you need to consider when doing the calculations for this curve.
- 2. Open up Excel and type in (or load) your data set. Convert the calibration mass into force by multiplying by g. This may be easiest to accomplish by adding an extra column to your spreadsheet to list the force value for each mass value.
- 3. Calculate the force each mass applies to the load cell using your torque balance equation from this week's tutorial. It may be easiest to create another column in your spreadsheet.
- 4. Plot the four data points in Excel, e.g. using a *Marked Scatter Chart*. The plot should have force on the y axis and voltage on the x axis.
- 5. The plot should be relatively linear. Under Excel's Chart Design tab, go to Add Chart Element -> Trendline -> Linear to add a trendline to the plot. Right click the trendline and select Format Trendline. Scroll to the bottom and click the Display Equation on Chart option to yield your calibration equation. You now have an equation that converts your measured voltage to a force.
- 6. Show your calibration curve to an instructor or proctor to confirm it is correct.

## 4.3 FMS Calibration

The goal of the FMS calibration is to construct a function that relates applied force to load cell voltage output. This will allow you to later convert measurements of the ROV mass, buoyancy, and motor thrust into units of Newtons. To accomplish this calibration, you will hang various masses on the top hook of the FMS and measure the mean load cell output voltage using a MyDAQ which speaks to LabVIEW.

1. At your FMS station, you should find a laptop running a VI named "P1C.vi". If it is not running, click the run button. This VI reads measurements from the FMS load cell via a myDAQ, as well as opening up a PWM control. Fig. 4 shows the two front panels. The load cell measurements are

plotted in real time (see chart with blue line). The mean value of the load cell data (using a moving window average) is displayed in a field just right of the chart.

A slider is used to control the PWM signal being sent to the thruster at the bottom of the FMS. See the right pane in Fig. 4. This won't be used until the next section.



Figure 4: The Front Panels that open when selecting P1C.vi.

 Be sure the vi is running, and press gently but firmly on the top-most horizontal beam that rests on top of the load cell. You should see the voltage level displayed in the chart respond to your pressure. An example of a typical LabVIEW output when force is applied to the FMS appears in Fig. 5.



**Figure 5:** Applying a downward force to the top beam of the FMS (a) to yield visible output on the LabVIEW VI (b).

3. Place the 500 g weight on the top hook. You might need a step stool for this. If you can't reach, ask a proctor or instructor for help. Wait for all motion in the system to dissipate and the voltage to reach a steady state value, i.e. the voltage tenths should not be changing much with time. Write down the mass being used, as well as the measurement displayed in the field labeled *Filtered Voltage* located on the front panel of the *P1C* vi, (see Fig. 6). Repeat this for the remaining weight values (e.g. 500g, 1000g, 1500g, 2000g).



**Figure 6:** The filtered voltage field located on the front panel of the vi P1C.

4. After repeating step 2 for all weights, you should have constructed a table listing masses and corresponding filtered voltage measurements. Show an instructor your table before moving on.

#### 4.4 Parameter Measurements

- To measure the ROV's mass, hang the ROV from the hook at the end of the top arm (see Fig. 7a). Make sure you attached the electronics box to your frame as well as the vertical thrust motor to get a good estimate of the ROV's mass in its final configuration. Also make sure none of the ROV is in the water during this measurement. Record the value displayed in the *Filtered Measurement* field.
- 2. To find the buoyancy of the robot, hook it onto the FMS lower arm as shown in Fig. 7b. This hook is underwater, so you will need to use a grabbing tool to submerge your robot and attach it to the hook. These are available in the test tank lab. Ask for help if you are not able to attach the robot to the hook. Once the ROV is attached to the lower arm, record the load cell voltage.



**Figure 7:** Finding the mass of the ROV (a) and the buoyancy (b) by attaching the ROV to the top and bottom hooks respectively on the FMS.

#### 4.5 Calibrating Motor Thrust

 Construct a motor thrust curve using the Digital – SW – Timed Output VI set up on the laptop. Adjust the duty cycle, which is the fraction of the motor's thrust we are commanding, from 25-75% in 10% intervals. Record the duty cycles and the corresponding load cell voltages from the field labeled *Filtered Voltage*.

You can try 100% as well. For some motors you may observe a phenomena called resonance which we will learn about in a few weeks.



**Figure 8:** Motor mounted at the bottom of the FMS.

## **5** Calibration and Force Extraction

In this section, you will need the methods presented in section 4.3 as well as data collected in the test tank room.

1. Use the set of calibration weight / voltage data points you measured to create a calibration curve relating voltage to applied force on the load cell.

- 2. Calculate the ROV's mass (kg) and buoyancy force (N) using the voltage measurements obtained in section 4.3 and the calibration curve equation from step 7. Remember that the calibration curve can be used to determine force measured on the load cell, and that the ROV's gravitational force was not being exerted directly on the load cell, (hint: remember your torque balance equations).
- 3. Make a plot of thrust force vs. duty cycle. Using Excel's trendline again, determine a linear model that relates duty cycle to thrust. Show your results to your proctor or instructor to confirm they are accurate.

#### **6 Updating the Simulator**

1. Modify the parameters in your simulator from practicum 1B to include the new experimentally determined values for mass and buoyancy. If you can't find your file, there are working simulator.vi files on Sakai under the *Module 1 Practicum C* folder.

Make sure you use mass in kg, and that your buoyancy value accounts for the fact that the FMS was measuring both the gravitational force and buoyancy when the ROV was submerged. Assume that the drag coefficient is 10 kg/s.



**Figure 9:** Modified simulator front panel with PWM signal scale on the slider control (a). In (b), an example of the corresponding block diagram.

- 2. Modify the simulator to include the linear model of thrust as a function of PWM signal, (see Fig. 10b). What happens when the PWM is set to 100%? What about -100%? Discuss what happens with an instructor or proctor.
- 3. Adjust your mass to achieve neutral buoyancy. Then, plot the vertical velocity of the ROV from this command sequence:
  - a. Set the thruster value to zero.
  - b. After a few seconds, change the thrust to 50%.
  - c. Wait until the ROV vertical velocity stabilizes close to some steady state value.
  - d. Stop the simulation and take a screen shot of your velocity (m/s) vs. time (s) plot.

#### 7 Reference List

- 1. Power supply data sheet http://www.mouser.com/ds/2/260/NES-150-SPEC-806295.pdf
- 2. MyDAQ manual <u>http://www.ni.com/pdf/manuals/373060f.pdf</u>

#### Appendix D: Comparison of learning outcomes and topics for original and redesigned course

#### **Original course learning outcomes:**

By the end of the course, students will be able to:

- Calculate the Fourier coefficients of a periodic signal.
- Calculate the frequency spectrum of an undersampled periodic signal and explain the aliased or folded frequency components.
- Translate the schematic of a linear time invariant (LTI) mechanical system of moderate complexity to the governing differential equations and reduce the differential equations to canonical form.
- Translate the schematic of a LTI electrical system of moderate complexity to the governing differential equations and reduce the differential equations to canonical form.
- Determine the transient-response characteristics from the governing differential equation of a 2nd-order system.
- Determine the frequency-response function from the governing differential equation of a 2nd-order system.
- Design a 2nd-order LTI system to meet a set of transient specifications.
- Design a 2nd-order LTI system to meet a set of frequency-response specifications.

#### Redesigned course learning outcomes:

By the end of the course, students will be able to:

- Model a linear time invariant mechanical system.
- Model a linear time invariant electrical system.
- Determine a system's transfer function and frequency response function.
- Determine the transient response of a linear time invariant system using transfer functions and Laplace transforms.
- Determine the frequency response of a linear time invariant system using frequency response functions and Bode plots.
- Design a stable feedback control system to meet transient specifications.

Original course modules	Redesigned course modules
(in order of presentation)	(in order of presentation)
Signal representation (in depth), including	Mechanical Systems
aliasing and folding	
Mechanical systems	Introduction to signals, including brief
	introduction to sampling, aliasing, and folding
Electrical systems	Transient response, including Laplace transforms
Transient response	Frequency response
Frequency response	Electrical systems
	Feedback control