The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #43523

Design and Assessment of a New Hardware-Based Dynamic Systems Course for a Mechanical Engineering Undergraduate Program

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Abstract

Many mechanical engineering undergraduate laboratory courses in dynamic systems and controls are primarily software-based, with laboratory assignments involving computer simulation modeling. While such simulation assignments may appeal to traditional mechanical engineering undergraduate students, especially male students, laboratory exercises that are hardware-based may appeal to a wider variety of students. In particular, the addition of physical experimentation should have an impact on male / female diversity, as there is some scientific evidence that female undergraduate students prefer kinesthetic learning to males, which involves moving the body and learning from the senses. In this work, a completely refurbished dynamic systems laboratory course is implemented into an undergraduate mechanical engineering program for the purpose of producing excellence in student learning and engagement. The new laboratory assignments involve physical experimentation, which is a modification to the previous course that included only simulation projects. Custom-made exercises include physical measurement and analysis of sound pressure signals, and reverse engineering of products using the Raspberry Pi compute platform. Coding of Raspberry Pi boards is accomplished using MATLAB Online and Simulink Online. Student engagement with both the new hardware-based course and previous simulation-based course are assessed using survey methodology, with a questionnaire deployed that includes short answer questions. The responses are inductively coded and reported in this work. Moreover, lessons learned from designing and assigning original dynamic systems physical experiments to mechanical engineering undergraduate students are highlighted.

1 Introduction

MECH-431, Dynamic Systems with Controls Laboratory, is a required course in the Mechanical Engineering (ME) undergraduate curriculum at Kettering University (KU). It is the companion laboratory course to MECH-430, Dynamic Systems with Controls, which is a lecture course. Both courses feature topics in classical control theory. Proportional-Integral-Derivative (PID) controllers are emphasized, as they are commonly used in industry and they are accessible to undergraduate students. MECH-430 and MECH-431 are normally taken in the same school term by KU students, as they are co-requisites. The MECH-431 laboratory course is currently in need of refurbishment. There are multiple controversial aspects to the course as it exists.

1.1 Existing Laboratory Course Concerns

MECH-431, comprised of nine laboratory assignments total, should be revised to include all new assignments. The new assignments should address and alleviate ongoing problems in MECH-431, including an overemphasis on simulation assignments, unwise investment in expensive and proprietary equipment, and repeated use of assignments with little modification. One aspect of MECH-431 that works well, however, is the requirement that students are expected to complete each laboratory assignment during class time. This requirement should be carried over into a revised version of the course. The class time restriction effectively forces students to focus on their work and not procrastinate.

1.1.1 *Overemphasis on Simulation Assignments*

MECH-431 relies heavily on the use of MathWorks® software, including both MATLAB® and Simulink®. This is a good thing, as these simulation software products are used extensively in industry by the companies that hire ME students. However, the MECH-431 laboratory course has evolved to encompass a series of in-class assignments that exclusively use software. This over-reliance on MATLAB and Simulink projects has downsides. The sole use of traditional computer simulation tasks can be boring for students, as prior research has shown that workshop environments are preferred for sparking student interest and engagement in their laboratory coursework [1]. Furthermore, the exclusive use of simulation assignments blurs the line between the MECH-430 lecture course and the MECH431 laboratory course, as similar simulation projects are assigned in both courses, raising questions about the need for a separate laboratory course.

1.1.2 *Imprudent Investment in Expensive and Proprietary Equipment*

MECH-431 was not always an exclusively simulation-based course. Around 2013, the course had some laboratory assignments that employed the Quanser QUBE™, which is a physical Direct Current (DC) electric motor with an associated controls teaching platform. That platform includes a suite of proprietary hardware, and it works in concert with LabVIEW™ software from National Instruments. By 2018, several of the QUBEs had ceased to function, out of an original set of ten units. That year, internal ME department research was conducted to investigate the cost of QUBE replacements. At that time the version of the QUBE owned by KU had been discontinued. According to Quanser, there were two QUBEs left (in their possession) from that outdated hardware generation. The ME department did not purchase those units, which ended the use of the QUBEs in MECH-431, as there would have been too many students in each laboratory group assigned to each remaining (functioning) QUBE.

Regarding the new generation of QUBE, a budgetary proposal in the range of tens of thousands of United States (US) dollars per QUBE unit was provided, depending on volume ordered. For reference, there are a minimum of 18 students enrolled (23 maximum) in each section of MECH-431. Even if two students are assigned to one QUBE, for a total of nine student QUBEs, and the instructor station has one QUBE for demonstration purposes, then the cost of a set of updated QUBEs would be in the hundreds of thousands of US dollars. That estimate does not include the cost of LabVIEW software and its annual maintenance fees, nor does it include the inevitable cost of hardware replacements. Clearly, the investment in expensive and proprietary hardware and software was imprudent for KU, which is a small, private, nonprofit, primarily undergraduate teaching institution with limited ME department funds.

1.1.3 *Repeated Use of Assignments with Little Modification*

Perennially, the simulation laboratory assignments of MECH-431 are reused, sometimes term-to-term with no changes. Usually, there are numbers that are changed in the assignments from one school term to the next. However, these changes are largely insignificant. This leads to an academic dishonesty problem with the students. Each term students are caught cheating by re-using laboratory assignments that were submitted by their peers in previous school terms, even though they are told explicitly that they are not allowed to do so. Unauthorized use of materials from previous school terms has become brazen among students, with some of them having “cribs” open on their computer displays from previous terms during class time, even though it is clear that the instructor is looking on. Other students have referred to cribs as their "reference materials", as a way of normalizing and justifying cheating, at least in their own minds.

While the responsibility for academic dishonesty lies primarily with the students, the MECH-431 course coordinator and instructors must bear some of the responsibility, as the course assignments have remained the same for years. For some students, the temptation to cheat is simply too great when a prodigious body of cribs is available for use. The solution to this problem will necessarily involve the creation of new laboratory experiments to be incorporated into a revised course, and the removal of old and overused exercises from the course.

2 Literature Review

The literature on the subject of laboratory experiments for undergraduate dynamic systems and controls courses shows that learning styles may be a factor in student learning and diversity. Specifically, female students seem to prefer learning through doing, and racially diverse students evidently benefit from project-based learning. This is especially true for students who were low performing before exposure to the project-based learning style. Several published studies have demonstrated how hands-on laboratory exercises can be implemented at low cost, and still be effective at improving student knowledge acquisition in controls and vibrations topics despite the limited investment of funds. Many of the original exercises created and reported in the literature have a cost of less than $150 US dollars per student, which may be affordable for many undergraduate institutions.

2.1 Student Diversity and Learning Styles

Wehrwein et al. [2] performed a study of learning style preferences in an undergraduate physiology laboratory course. Students completed a questionnaire that identified their preferences for for four different learning styles: 1) visual, 2) aural, 3) read-write, and 4) kinesthetic. The students voluntarily indicated their gender in the questionnaire. The results of the study showed that male and female students have significantly different learning styles. Most male students (58%) preferred a combination of all four learning styles, whereas most female students (54%) preferred a single mode of instruction, which in the majority of cases was kinesthetic. The kinesthetic learning style highlights physical experiences, such as performing an activity with touching and manipulation of objects. Therefore, a laboratory course that involves physical experimentation is likely to be perceived as especially engaging by female students, who prefer to learn through doing. The experimental type of laboratory course should also appeal to male students, although to fully engage male students the instruction of the course should embody additional modes of learning such as visual, aural, and read-write.

Han et al. [3] investigated project-based learning activities in Science, Technology, Engineering, and Mathematics (STEM) subjects in high schools. Specifically, STEM activities were deployed at three high schools in urban, low-income communities in Texas in the US, and the effect of the activities on student mathematics scores over three years on a standardized test were studied. Students participating in the study were 54% Hispanic and 38% African American, with the remainder made up of White and Asian students. Overall, the student body was 49% male. Thus, the student participants were racially and gender diverse. Interestingly, the lowest performing students showed the biggest improvement in mathematics scores after having experienced project-based learning, suggesting that the use of this learning style is effective at decreasing achievement gaps in student performance in low performing groups compared to middle and high performing groups. Similarly, Busyairi et al. [4] studied project-based learning in a university setting with students training to be physics teachers. In that case, project-based learning was found to improve student exam scores and the ability of students to prepare research proposals.

Zhang et al. [5] developed an undergraduate chemical engineering laboratory course with experiential learning exercises. The course was designed to include open-ended assignments that employed project-based learning, particularly with experiments designed by the students themselves. The idea was to teach students how to design and conduct experiments, as well as enhance student enthusiasm and interest, with the goal of increasing knowledge and developing critical thinking and problem-solving skills. The course retained traditional direct instruction for knowledge transfer about equipment and laboratory procedures. Likert-style surveys were given to the students, so they could provide feedback about the project-based learning style versus traditional learning styles. Overall, the students reported that the project-based learning approach was more effective than the traditional method in acquiring critical and creative thinking skills. The authors noted in conclusion that both traditional and project-based learning styles can be effective in laboratory courses, and they suggested that each style could be used separately in a two-course undergraduate laboratory course series, with the traditional method employed at the junior level, and the project-based approach used at the senior level.

2.2 Hands-On and Low Cost Laboratory Exercises

Utschig et al. [6] pointed out the "need for hands-on, inquiry-based experiences in dynamics, vibrations, control theory" in undergraduate ME programs. They also noted that budget constraints are one of the hurdles that educators must overcome when implementing such hands-on laboratory exercises. To address the cost issue in undergraduate vibrations and controls courses, this study investigated the effectiveness of inexpensive physical experiments. Several experiments were manufactured that exploited low-cost 3D-printing techniques. For example, two of the experiments created were 1) a translating carts mechanism, and 2) a pendulum with varying tip loads. Each experimental setup cost around $50 US dollars to produce per student, which was much less than the cost associated with buying ready-made experimental setups from outside educational equipment suppliers. Results from student surveys deployed both before and after the laboratory excercies showed that most students (60%) who completed the inexpensive hands-on learning activities reported that the activities supported their learning "a lot" or "a great deal". Therefore, this study demonstrated that low-cost, hands-on activities deployed to students in a dynamic systems laboratory course can be beneficial to their learning.

Torres-Salinas et al. [7] developed a laboratory controls course around fuzzy control of a DC electric motor. Students were required to design and build a physical test platform including the DC motor, a data acquisition system and related hardware, and perform the programming of a fuzzy logic controller for angular position control of the motor shaft. The student outcomes from this hands-on controls course were evaluated, with the results showing improved student grades compared to purely simulation-based learning.

Rojko et al. [8] observed that it is beneficial for students to test their control system designs on real systems, and not exclusively perform simulations. As they mentioned, the "design of mechatronics control systems is one of the areas where computer simulations without experimental verification are highly questionable, maybe even useless". In their study, remote experiments were designed for students at a group of European universities, wherein the students engaged with real dynamic systems even though they were not physically present in the laboratory. In one course assignment, a mechatronic system with a spring was position controlled by the students using various linear and nonlinear controllers. Students contacted the remote laboratory through an internet web page interface, which provided live system response measurements and video footage of the system during operation. Students who participated in the remote laboratory experiments were surveyed after the course. The results of the study showed that while most of the students (72%) thought that remote laboratory experiments were a suitable way to acquire new knowledge of controls, a minority of students (22%) felt that such remote exercises could totally replace local, hands-on controls experiments. Therefore, there appears to be real learning value to students in actual hands-on engagement with dynamic systems in a laboratory environment.

Gunasekaran et al. [9] developed a low-cost hands-on experiment for an undergraduate electrical engineering laboratory course. The experiment involved the development of a permanent magnet DC motor control strategy that was microcontroller-based. The total hardware cost per student was around $80 US dollars. Student surveys from the laboratory course showed that 89% of the students felt that the exercise helped them to understand fundamental principles, which were introduced in a previous lecture course about control systems theory.

Aviles et al. [10] developed a ball and beam controls experiment for an undergraduate laboratory course, which was comprised of position control of a DC motor, as well as position control of a ball on a rail. The experiment was designed with readily available materials. The total cost of the materials per student was $128 US dollars. The experiment was designed based on the requirements of the Accreditation Board for Engineering and Technology (ABET) student outcomes for ME programs [11], encompassing the need for students to solve complex engineering problems and practice the engineering design process. This study demonstrated that an ABET consistent laboratory controls experiment can be created that employs commonly available materials at low cost.

3 Revised Laboratory Course

The purpose of this study is to create a series of new assignments for a revised MECH-431 laboratory course at KU, and evaluate their effect on student learning and engagement. These assignments involve physical experimentation, and they employ inexpensive equipment that is commonly available or already in place at KU. The new assignments, and their derivatives, are designed to inject fresh content into MECH-431, minimizing the value of cribs and mandating student engagement. The new assignments employ discovery-based learning, including hands-on encounters with physical materials and equipment. Furthermore, they feature open-ended problems with multiple solutions. The newly refurbished MECH-431 laboratory course is designed to appeal to a variety of students, as it incorporates the performance and design of physical experiments and dynamic systems into a previously purely simulation course.

3.1 New Assignments

Two of the new laboratory assignments created for the revised MECH-431 course are described here. One is performed in the HEAD acoustics Lab, and the other is performed in the Denso Lab.

Both laboratories are located on the campus of KU.

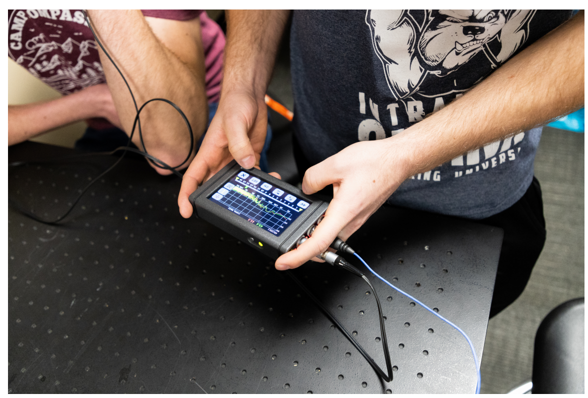
3.1.1 Measurement, Analysis, and Filtering of Physically Measured Sound Pressure Data

This laboratory assignment is performed over two laboratory class periods in the HEAD acoustics Lab (first class for data acquisition) and the Denso Lab (second class for data analysis held one week after the first class). Details about this assignment are provided in Appendix A. The purpose of the assignment is to teach students how to perform the following:

1. Analyze dynamic systems in the time and frequency domains. Analysis may include calculation of natural frequencies, damping ratios, and bandwidth.
2. Design and implement filters using Bode plots.

In this laboratory assignment series, students perform the entire process of measuring, analyzing, and filtering real sound pressure signals. Such measured data are more complex that the noise-free and "perfect" signals that are produced by simulations. The process of recording physical sound pressure data and confirming its validity is a valuable experience for ME students, who may not have an opportunity to do so either through other courses in the ME curriculum or at their co-operative employment jobs. The new laboratory assignment is conducted in the HEAD acoustics Lab, which is a new laboratory at KU that has recently finished construction. The HEAD acoustics Lab features equipment and software for sound pressure measurement and data analysis. Photographs showing the HEAD acoustics Lab appear in Figure 1. Note that there are three data acquisition areas in the HEAD acoustics Lab, two in small rooms (formerly faculty offices), and one in a main common area.

(a) Main Experiment Station



(b) Portable Data Acquisition System

Figure 1: HEAD Acoustics Lab Facilities for Sound Pressure Measurement Exercise

As there are three experiment setup areas in the HEAD acoustics Lab, each section of MECH-431 is divided into three groups of students. The typical class size for MECH-431 is 18 students per section, so each experiment area has about six students. Most of the data acquisition equipment and software required for MECH-431 in the HEAD acoustics Lab is already in place and owned by KU. The only remaining equipment to be added was a desktop computer for each of the three experiment setups. The three computers were previously used in a different ME course, and they were donated by the ME department.

3.1.2 Reverse Engineering the Lovebox® using Raspberry Pi

This laboratory assignment is performed over several laboratory class periods in the Denso Lab. Details about this assignment are provided in Appendix A. The purpose of the assignment is to teach students how to perform the following:

1. Validate a mathematical model using experimental data collected from hardware.
2. Evaluate engineering system performance characteristics such as stability, time to steady-state, and Maximum Percent Overshoot (MPO).
3. Develop a controller (e.g., Proportional (P), Proportional-Derivative (PD)) for an engineering system and test it on hardware.

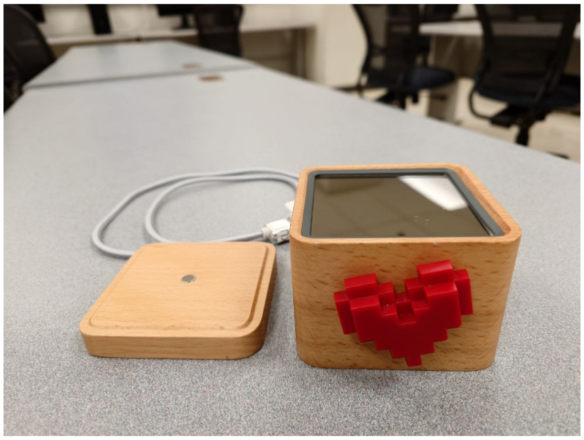
The Lovebox [12] is a messaging device that facilitates communication between people. It is primarily used by families to communicate with elderly or infirm relatives who are living in care homes. The Lovebox was a useful tool for one of the authors at the beginning of the COVID-19 pandemic, when an elderly relative could not receive personal visitors due to their assisted living facility being locked down. The Lovebox was used to send messages to the relative in the facility. The Lovebox functions according to the following procedure:

1. The sender transfers a message or photograph to the Lovebox using a smartphone app.
2. A red plastic heart on the front of the Lovebox spins, letting the receiver know that a message is waiting.
3. The top of the box is removed by the receiver to reveal the message. The plastic heart stops spinning.
4. An automated read receipt is delivered to the sender when the top of the box is removed.
5. The receiver can send an emoji reaction to the sender's app consisting of a "waterfall of hearts" by spinning the plastic heart.

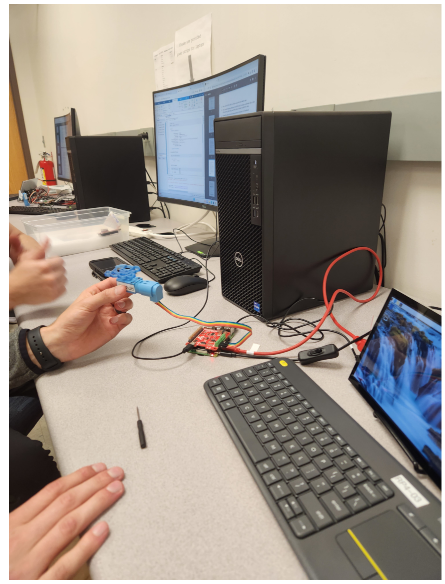
A new MECH-431 laboratory assignment was designed with the goal of having students create their own messaging system based on the Lovebox. The students build and control a "Bulldog Box" (a bulldog is the mascot of KU) using a Raspberry Pi 4 Model B 4GB Single-Board Computer (SBC), a 7" LCD display screen, a keyboard and mouse, an Auto pHAT motor driver, a DC motor with encoder, and a 3D-printed motor shaft attachment in the shape of a bulldog. The total cost of materials for all enrolled students is about $6,000 US dollars. Photographs of a Lovebox and the Raspberry Pi hardware are shown in Figure 2. This laboratory assignment gives the students an opportunity, and the confidence, to reverse engineer systems they may find at home or work. It provides them with an entry point to learning about the possibilities of creating their own low-cost control systems, as well as developing much more complex control systems.

3.2 MATLAB Online and Simulink Online

An added complexity in the implementation of the Lovebox reverse engineering exercise is the use of MATLAB Online and Simulink Online to program the Raspberry Pi boards in MECH-431. The decision to use the Online versions of these software products was motivated by the goal of consistency, both in terms of software version and software performance. In the past, students would bring their personal laptop computers to the laboratory with various versions of MATLAB and Simulink software installed, even though they were specifically asked to install the particular version that was being used in the course. This created problems, as many of the file types saved



(a) Lovebox With Red Plastic Heart



(b) Raspberry Pi and Accessories

Figure 2: Lovebox and Raspberry Pi Hardware for Reverse Engineering Exercise

by the software are incompatible with older versions of the software. The file format incompatibility meant that the students could not share files with the instructor or other students.

Another concern with local installation of MATLAB and Simulink software on personal laptop computers is their high computational requirements. Significant storage space is required to download and install the software, and computer hardware requirements during typical software use have become significant with recent versions. Some students have not been able to afford the financial cost of investing in a computer that meets the hardware requirements of the software. Furthermore, the ME department at KU is having trouble covering the cost of modern desktop computers for walk-up use in its laboratories.

The version incompatibility and hardware cost issues led to the exlusive adoption of MATLAB Online and Simulink Online in MECH-431. These are the web browser-based versions of the software, where a remote computer (with the software installed) is contacted and employed via a local web page interface. Many modest laptop computers and walk-up workstations can employ MATLAB Online and Simulink Online, as the calculations made by the software are done remotely, with the local computer acting solely as a graphical interface. Use of MATLAB Online and Simulink Online also eliminated the file version problem, as everyone who is using the software is necessarily using the same software version.

MATLAB and Simulink can both be used to program Raspberry Pi boards. There are two possible modalities for communication between the software and a Raspberry Pi [13]. In the first case that can be described as “Connected Input / Output”, the Raspberry Pi is tethered to a computer running MathWorks software. In this case the Raspberry Pi board is under the remote control of the MathWorks software. This modality is used for development and debugging of algorithms on the Raspberry Pi. The second case can be described as “Deployment”, which involves C code generation and code transfer to the Raspberry Pi board itself. In this case there is standalone execution of code on the Raspberry Pi hardware, normally after the code is finalized for use in a particular application.

Typically a local workstation running MATLAB and Simulink is used during the first phase of code development, when the Raspberry Pi board is connected to the workstation. In this scenario, both the local workstation and the Raspberry Pi board must be connected to the same network. Based on direct experience during this study, the connected workflow works well as long as both devices are connected to the same stable network. However, the use of MATLAB Online and Simulink Online present additional difficulties when programming Raspberry Pi boards, as there are multiple networks involved and added latencies. Moreover, the Wi-Fi network in the Denso Lab at KU is unsteady, adding further complications. Fortunately, MathWorks engineers helped the instructors to get MATLAB Online and Simulink Online working with Raspberry Pi boards before the revised course began and during its first execution in the Spring school term of 2023.

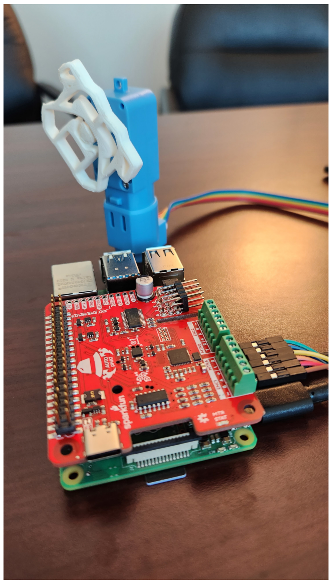
3.3 Equipment and Budget

Table 1 lists the items in each MECH-431 Raspberry Pi laboratory kit and the cost for each item. The total cost for each kit is about $300 US dollars. In the MECH-431 classroom there are typically 18 students per course section. There are also two instructors who teach the course in one school term. Therefore, the total cost of materials, assuming 20 kits are needed is 20 $\times$ $300 USD = $6,000 USD. This is the materials cost for the Raspberry Pi reverse engineering exercise only. The cost of MathWorks software and licenses is excluded, as the institution already pays for that separately. Also excluded is the cost of acquiring the HEAD acoustics sound pressure data acquisition equipment and ArtemiS SUITE software, as those had been obtained previously as in-kind donations to the institution.

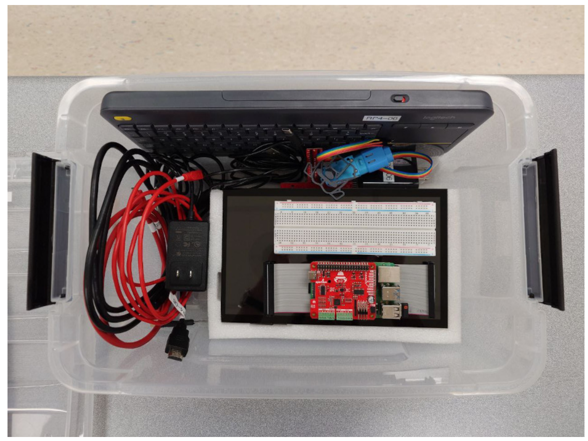
Table 1: Raspberry Pi Hardware Kit Shopping List and Cost

Item No.	Item Description	Cost Per Item (USD)
1	Raspberry Pi 4 Hardware Starter Kit - 4 GB [14]	$171.50
2	Raspberry Pi Pinout Reference Board [15]	$1.50
3	Raspberry Pi Camera Module V2 [16]	$25.00
4	Auto pHAT Motor Driver [17]	$32.50
5	Touch Screen 7 Inch HDMI Display [18]	$37.97
6	Hobby Motor with Encoder [19]	$7.95
7	Generic High Torque Servo Motor [20]	$13.95
8	Rotary Potentiometer [21]	$1.05
9	Silver Metal Knob [22]	$1.60
10	Full-Size Breadboard [23]	$6.50
11	Clear Plastic Protractor [24]	$0.26
	TOTAL	**$299.78**

Figure 3 shows photographs of the Raspberry Pi hardware kit for use in the reverse engineering exercise, including a detailed view of the Raspberry Pi board with the Auto pHAT daughter board installed. In the photograph, the Raspberry Pi board is green in color and located underneath. The Auto pHAT daughter board is red in color and located above. The hobby motor is blue in color, with a bulldog motor shaft attachment that is white in color.



(a) Raspberry Pi with Auto pHAT and Hobby Motor



(b) Hardware Kit

Figure 3: Raspberry Pi Hardware Kit for Reverse Engineering Exercise

4 Research Methodology

Survey methods in research were applied in this study. A survey was deployed to MECH-431 students at KU in 2023 who were enrolled in the Winter (January through March) and Spring (April through June) school terms. The survey was the same in both terms, and it was voluntary. MECH-431 students completed the survey near the end of each school term, with the Winter term surveys completed in March 2023, and the Spring term surveys completed in June 2023. The MECH-431 courses were complete by the time the survey was taken by enrolled students, so they were able to reflect on the course as a whole at the time of completing the surveys.

4.1 Hypothesis

Results are determined in this study by inductive reasoning. Based on the results of the literature review, it is clear that some dynamics systems and controls undergraduate laboratory courses at other institutions have effectively employed hands-on laboratory exercises at low cost. Therefore, a reasonable resulting hypothesis is that low cost physical laboratory experiments can be employed effectively in undergraduate engineering teaching laboratories in general, and that this hypothesis is specifically true in the case of MECH-431 at KU. The published literature also suggests that hands-on laboratory exercises should particularly appeal to female students versus male students. This study did not explicitly investigate a hypothesis surrounding male / female diversity, due to a relatively small number of female survey participants. Regardless, responses from female students versus male students are highlighted where they are notably different.

4.2 Survey Questions

Table 2 lists the student survey questions. The survey was deployed online using Google Forms. Eight questions were asked on the survey, with one dropdown question, four multiple choice questions, one linear (i.e., Likert / rank ordered) scale question, and two paragraph questions.

Table 2: Student Survey Questions

No.	Prompt	Type	Notes
1	What semester were you enrolled in MECH-431?	Dropdown	Two options given: 1) Winter 2023 and 2) Spring 2023.
2	Please identify your gender.	Multiple choice	Three options given: 1) Female, 2) Male, and 3) Other, with a fillable field that could be used to provide more information.
3	Please identify your major.	Multiple choice	Three options given: 1) ME, 2) EE, and 3) Other, with a fillable field that could be used to provide more information.
4	Do you enjoy hands-on encounters with physical materials and equipment?	Multiple choice	Three options given: 1) Yes, 2) No, and 3) Does not matter.
5	Did MECH-431 incorporate hands-on encounters with physical materials and equipment?	Multiple choice	Two options given: 1) Yes and 2) No
6	How would you rate your exposure to hands-on encounters with physical materials and equipment in MECH-431?	Linear scale	Five buttons given, from 1) Not enough hands-on encounters to 5) Excessive hands-on encounters.
7	What was your favorite lab assignment and why?	Paragraph	Fillable field provided for long answer text.
8	What was your least favorite lab assignment and why?	Paragraph	Fillable field provided for long answer text.

5 Results and Discussion

Overall, the results from the student surveys show that the students enjoyed the revised course more than the previous course. Students overwhelmingly recognized that the revised course incorporated hands-on encounters with physical materials and equipment, especially in comparison with the previous course. Students also indicated that the revised course contained an appropriate level of hands-on exercises. They particularly appreciated the Lovebox reverse engineering assignment near the end of the revised course, recognizing its comprehensive nature.

5.1 Response Analysis by Plotting and Visualization

Student responses to the multiple choice and linear scale questions were analyzed using plotting and visualization approaches. Specifically, responses to questions about gender and hands-on encounters with physical materials and equipment were analyzed using bar graphs and pie charts.

5.1.1 Gender of Participants

Figure 4 presents a bar chart showing the gender makeup of the student survey participants. All the students responded either "Female" or "Male" as their gender. None of the students indicated "Other" as their gender. In Winter term there were 39 students who completed the survey, with 18% (7/39) being female and the remainder being male. In Spring term there were 42 students who completed the survey, with 26% (11/42) being female and the remainder being male. Overall, there were 81 students who voluntarily completed the survey over both terms, with 22% (18/81) of them being female. This is a very typical gender mix in engineering programs, which on average has been around 22% women and 78% men for the last five years [25].

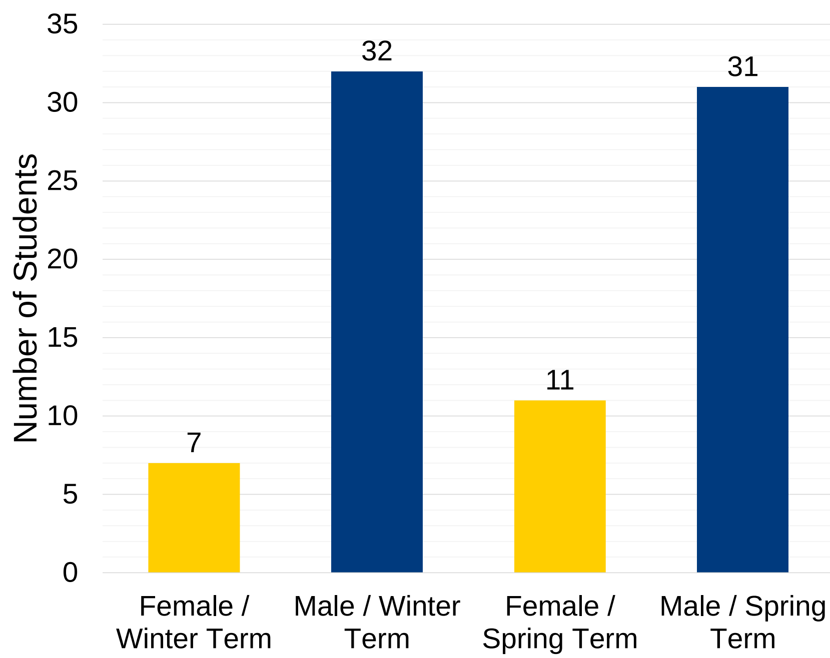


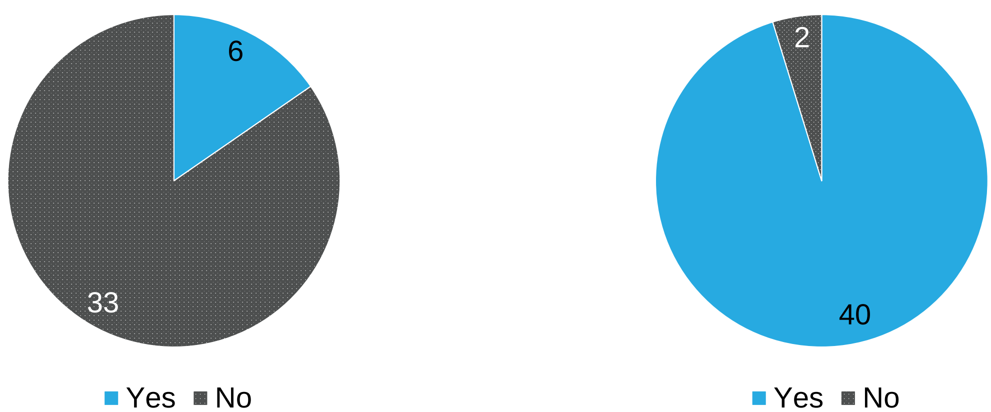
Figure 4: Responses to the Question "Please Identify Your Gender"

5.1.2 Academic Major of Participants and Enjoyment of Hands-On Exercises

ME was the major area of study for all the students who completed the survey. In Winter term there were two dual-major students, both with ME as one of their majors. The first student was studying ME and Industrial Engineering (IE), and the second student was studying ME and Engineering Physics (EP). There were no dual-major students in Spring term. In answer to the question "Do you enjoy hands-on encounters with physical materials and equipment?", almost all students (80/81) replied "Yes", with one student (1/81) in the Winter term replying "Does not matter". Interestingly, the outlying student who replied in the single minority was the ME/IE dual-major, and this student was also female. While no reason for explaining the response to the hands-on exercises question was solicited by the survey, it is possible that the IE program at KU has other opportunities for hands-on experimentation, rendering the matter less important for that one particular student.

5.1.3 Incorporation of Hands-On Exercises

Figure 5 graphs the responses to the question “Did MECH-431 incorporate hands-on encounters with physical materials and equipment?” for two school terms. In the Winter term, 85% (33/39) of students responded negatively, indicating that the course did not incorporate hands-on exercises. This is the expected result, as the Winter term MECH-431 course was the legacy version of the course, with only simulation assignments. As to the 15% (6/39) of students who responded positively, it is unknown which aspects of the previous course they perceived as hands-on. As the previous course was heavily computer simulation-based, it is possible that these students could have thought of interaction with a computer as a hands-on exercise. Also shown in Figure 5 are the student responses from the Spring term. The overwhelming majority of students, 95% (40/42) responded positively, recognizing the addition of the hands-on sound pressure measurement and reverse engineering exercises to the revised MECH-431 course.



(a) Winter Term / Previous Course **(b) Spring Term / Revised Course**

Figure 5: Responses to the Question “Did MECH-431 Incorporate Hands-On Encounters with Physical Materials and Equipment?”

5.1.4 Level of Exposure to Hands-On Exercises

Students were presented with a Likert question in the survey, specifically “How would you rate your exposure to hands-on encounters with physical materials and equipment in MECH-431?”, with a one-to-five scale. One on the scale represented “Not enough hands-on encounters”, whereas five on the scale represented “Excessive hands-on encounters”. The desired result (from the perspective of the instructors) would be to have most students select three (on the linear scale), which would represent a balance between not enough hands-on encounters and excessive hands-on encounters, where excessive would indicate more hands-on experiments than necessary or desirable.

Responses to the Likert question are presented in a bar chart in Figure 6. From Figure 6 it can be seen that most students surveyed in the Winter term thought that the previous course did not have enough hands-on exercises, as the majority of students, 74% (29/39), chose either one or two on the linear scale, which were the choices available on the "not enough" side of the scale. Therefore, students in the previous course noticed the deficiency in the course, that it was lacking in hands-on laboratory experiences. In contrast, most students in Spring term thought that the revised course had a reasonable amount of hands-on exercises, as the majority of them, 76% (32/42), chose either three or four on the linear scale. Thus, most students in the revised course recognized the incorporation of hands-on exercises into the course. Curiously, three of the students in the revised course felt that there was an excessive amount of hands-on experiences in the course. All three students were male. It is possible that these male students prefer learning styles other than kinesthetic. Overall, results from the Likert scale question confirm that the revised course has about the right level of exposure to hands-on experiences.

Figure 6: Responses to the Question "How Would You Rate Your Exposure to Hands-On Encounters with Physical Materials and Equipment in MECH-431?"

5.2 Response Analysis by Inductive Coding

Student responses to the paragraph questions were inductively coded [26]. Specifically, the long answers to the questions "What was your favorite lab assignment and why?" and "What was your least favorite lab assignment and why?" were inductively coded. The responses were coded according to response categories that emerged during the survey data analysis. Note that the example responses from student surveys are presented here verbatim, exactly as they were written by the students. No redacting of student survey responses was performed.

5.2.1 Favorite Laboratory Assignment – Winter Term

Table 3 shows the results from coding the favorite laboratory assignment responses for Winter term. This was for the previous MECH-431 course that was exclusively simulation-based. Four categories resulted from coding the response data for Winter term. Of those four categories, three lab assignments were selected by the students as favorites. Two of these favorite assignments, "Filtering Engine Mount Acceleration Data" and "PD Control of an Automotive Suspension When Traversing a Frost Heave" had similar reasoning supplied as to why they were preferred as favorites. In both cases, the favorite assignments had a practical component or real-world application to them.

The most favored assignment was selected by more than one-third of the students, or 38% (15/39). This was the "Filtering Engine Mount Acceleration Data" exercise. The assignment involved processing acceleration data that the course instructors had measured at the engine mounts of an off-highway vehicle previous to the course. The frequency range of the acceleration measurement was such that the data had an audible component. The exercise involved filtering the acceleration data in MATLAB, then comparing the filtered data with the unfiltered data by analysis in the time and frequency domains, and by listening. Students seemed to appreciate the clear and useful demonstration of filtering provided by this assignment.

Table 3: Categories for the Question "What was your favorite lab assignment and why?" in Winter Term

[a] DS2 is a name for MECH-431 and [b] DS1 in a name for MECH-331. DS1 is the prerequisite course for DS2.

Category (Lab Description / Reasoning)	**Sample Response**	**Count**
Filtering Engine Mount Acceleration Data / Audible Results of Filtering	"Filters lab because we had something a bit more tangible (ie a sound) that we could actually see/hear the result of"	15
PID Control of a Plant Using Ziegler-Nichols Ultimate Cycle Method / Graphical Visualization of Responses	"Favorite lab assignment was the one where we changed up the PID controller because it actually allowed me to see graphically how a system would respond and how i could control it."	14
PD Control of an Automotive Suspension When Traversing a Frost Heave / Practical Application	"I enjoyed the control assignment for the vehicle suspension, because it offered a tangible system that I could visualize. It would be nice if there was some way to make the other labs have a real-world outcome that the students can witness live, rather than a somewhat ambiguous graph."	5
None of the Labs / No Hands-On or Physical Exercises	"I cant really say that i had a favorite. Not trying to be negative, but DS2[a] labs have been some of the worst labs ive been in at Kettering. DS1[b] was better, as some of the labs required some hands on to supplement the coding"	5
	TOTAL	**39**

Another assignment that was preferred by some of the students as a favorite, 13% (5/39), due to its practical nature was "PD Control of an Automotive Suspension When Traversing a Frost Heave". In this assignment a quarter-car model was exercised to simulate suspension control when an automobile traveled through a pothole. The assignment was enhanced with a short video shown to the students at the start of class. This video was filmed on one of the worst condition two-lane roads in the US, with extensive broken pavement resulting in cars and trucks experiencing violent vehicle motions. The assignment resonated with the students as a practical example of what can be done with controls.

Somewhat surprisingly, the second most favored assignment at more than one-third of the responses, 36% (14/39), was "PID Control of a Plant Using Ziegler-Nichols Ultimate Cycle Method", which was a pure simulation exercise. The plant to be controlled was not described physically, but instead it was represented as a transfer function in the Laplace domain. Despite the mathematical and theoretical nature of the assignment, students generally liked it. The main task of the assignment was to plot and visualize the responses of a PID controlled system. The graphing aspect of this simulation assignment evidently appealed to students. There were some students, 13% (5/39), who chose not to list a favorite laboratory assignment. Most of the reasoning provided was related to a lack of hands-on exercises in the course. Thus, the deficiencies in the course were apparent to both the students and their instructors.

5.2.2 Least Favorite Laboratory Assignment – Winter Term

Table 4 shows the results from coding the least favorite laboratory assignment responses for Winter term. Four categories resulted from the coding of student responses to the question prompting them for their least favorite laboratory assignments. Peculiarly, the top three least favorite assignments were also the same as the top three favorite assignments, although for different reasons. These three assignments clearly made an impression on the students. The fourth category that resulted from the least favorite lab question was "Most of the Labs", which was similar to "None of the Labs" for the favorites question.

Table 4: Categories for the Question "What was your least favorite lab assignment and why?" in Winter Term

Category (Lab Description / Reasoning)	Sample Response	Count
PD Control of an Automotive Suspension When Traversing a Frost Heave / Lack of Knowledge Due to Missed Lecture	"Lab 8 because we had missed a day of class so the knowledge needed for the lab was not there."	20
Most of the Labs / Lack of Documentation or Practical Applications	"Most of them, honestly. We didnt have anything physical to interact with, we were just making numbers on a graph move. A physical system that we had to work with would've been really cool."	13
Filtering Engine Mount Acceleration Data / Difficulty With Filtering Process	"Lab 6. I couldn't get my filter to work correctly and I couldn't figure out why. Perhaps I needed more preperation from coursework."	3
PID Control of a Plant Using Ziegler-Nichols Ultimate Cycle Method / Exercise Was Too Long	"The last lab was my least favorite. It seemed very tedious at times. The content was good but the process was long."	3
	TOTAL	**39**

The least favorite laboratory assignment in Winter term was by far "PD Control of an Automotive Suspension When Traversing a Frost Heave", although that was mostly due to an anomaly in the execution of the course in the Winter term of 2023. The institution was shut down due to dangerous winter weather for one day, which was the same day that a lecture in the companion course (MECH-430) was going to be given on the topic of PD control, specifically to prepare the students for the automotive suspension laboratory exercise. Therefore, most of the students complained that they did not have the necessary preparation to properly understand and perform the assignment. Based on this experience, laboratory exercises that rely on related lecture content to provide background should be delayed if the lecture class does not happen before the laboratory class. Many students, 51% (20/39), complained about lack of preparation for this particular exercise.

A few students, 8% (3/39), had trouble with the "Filtering Engine Mount Acceleration Data" and the "PID Control of a Plant Using Ziegler-Nichols Ultimate Cycle Method" assignments, listing them as their least favorite. Generally, students had trouble completing these exercises during class time, and in some cases they had difficulty completing the task successfully, such as in the case of the filtering exercise. It is possible that a smaller laboratory class size could help, as this would allow for more instructor time with each student. In Winter term there were 39 students spread across two course sections. In general, enrollment is in the range of 18 to 23 students for each section of the MECH-431 course. For some sections, depending on enrollment, the instructor may not be able to spend enough time with each student to help them make a success of their assignment and encourage them to finish on time. A smaller class size might help the minority of students who struggle with the assignments.

One-third of the students, 33% (13/39), stated that "Most of the Labs" were their least favorite. The reasoning supplied was mainly along the lines of the lack of physical experimentation in the laboratory exercises. This mirrored the responses from the most favorite question, where some students lamented the lack of hands-on exercises in the course.

5.2.3 Favorite Laboratory Assignment – Spring Term

Table 5 shows the results from coding the favorite laboratory assignment responses for Spring term. This was for the revised MECH-431 course that was based on physical experimentation and hands-on exercises. Only one simulation exercise was carried over from the previous course, the "PD Control of an Automotive Suspension When Traversing a Frost Heave" lab. This assignment was carried over since it addressed an important course topic, PD control. The carry-over assignment was also used to see how a pure simulation exercise would be received by students who were taking a laboratory course that was otherwise based on hands-on experiments. There were nine laboratory assignments total in the revised course, which was the same number as the previous course. Students were expected to complete each assignment during laboratory class time, which also remained the same compared to the previous course.

From Table 5 it can be seen that a sizable minority of students, 45% (19/42), reported that the (chronologically) last laboratory assignment of the course was their favorite, "Reverse Engineering of the Lovebox". One common theme that came from the coding process related to this assignment was the idea of combination or consolidation of learning. To be sure, the instructors expected the reverse engineering exercise to be interesting to students. However, it is

Table 5: Categories for the Question "What was your favorite lab assignment and why?" in Spring Term

Category (Lab Description / Reasoning)	**Sample Response**	**Count**
Reverse Engineering of the Lovebox / Combination of Learned Principles	"My favorite lab assignment was the last lab, where we took concepts from many different weeks and combined them to make the heart box code and functions."	19
Controlling a DC Motor With Raspberry Pi / Seeing Physical Results of Coding	"My favorite lab assignments were from weeks 5 and 6. This is because it was my first time using a raspberry pi and being able to deploy code to it in order to get a motor to spin was a lot of fun. Overall this has been the best lab I have had at kettering."	12
Acquisition of Sound Pressure Measurements / Exposure to Measurement Equipment	"I enjoyed going to the HEAD acoustics lab and recording things on different equipment. It was cool to become familiar with the different equipment and become more skilled with audio recording."	6
None of the Labs / No Reason Given	N/A	3
PD Control of an Automotive Suspension When Traversing a Frost Heave / Close Relationship to Lecture Material	"The week 7 lab where we tuned a PID controller. It felt the most applicable to what we were learning."	2
	TOTAL	**42**

somewhat surprising that the students clearly recognized that the assignment was designed to use all their previous knowledge from the course. Specifically, the reverse engineering exercise required coding of the Raspberry Pi board using MATLAB Online and Simulink Online, position control of a DC motor, using encoder measurements as part of a feedback control strategy, and coding of logic in conditional statements. The assignment was designed to be comprehensive, and many students recognized and appreciated this.

Some students, 29% (12/42), reported that the "Controlling a DC Motor With Raspberry Pi" assignment was their favorite exercise. This assignment occurred about halfway through the course. It introduced students to motion control of the DC motor shaft and reading of encoder output. The laboratory exercise from the previous week involved becoming familiar with programming a Raspberry Pi with MATLAB Online and Simulink Online, by blinking the Raspberry Pi board's on-board Light-Emitting Diode (LED). None of the students listed the LED blinking exercise as their favorite laboratory assignment. It appears that turning on lights is not enough activity for ME students, who evidently prefer to make things move. The desire of ME students to engage in hands-on laboratory exercises was reinforced by those who reported the "Acquisition of Sound Pressure Measurements" as their favorite assignment, at 14% (6/42). This assignment involved making sound pressure measurements of an inexpensive metronome with three different data acquisition systems of widely varying quality. Thus, some students in the course enjoyed learning about physical acoustic measurement methods. This was not a guaranteed result, as acoustics is not typically a ME subject.

5.2.4 Least Favorite Laboratory Assignment – Spring Term

Table 6 shows the results from coding the least favorite laboratory assignment responses for Spring term. Six categories resulted from the coding of student responses to the question prompting them for their least favorite laboratory assignment. The assignment that resulted in the most unfavorable reviews was the "PD Control of an Automotive Suspension When Traversing a Frost Heave" carry-over simulation exercise. More than one-third of the students, 36% (15/42), reported that this assignment was too long to complete in class time. Furthermore, many students complained that this assignment was a simulation exercise only, which is a comment that was not observed in Winter term. It is interesting to note that the pure simulation nature of the exercise stood out in the surroundings of the revised course, whereas this aspect went unnoticed in the previous course.

Another laboratory assignment that was selected as a least favorite in Spring term was "MATLAB and Simulink Basics", which included a custom-designed review of software concepts, as well as completion of online software training courses from MathWorks. For about one-quarter of students, 26% (11/42), the software training was reported as being boring compared to the hands-on exercises used in the majority of assignments in the course. However, this laboratory assignment, which was carried over from the previous course, garnered no negative attention in the previous course. It was apparently tedious in comparison with the physical experiments in the revised course, though.

Some students, 12% (5/42), did not name a least favorite laboratory assignment. These students responded that each assignment served a learning purpose. A few students, 7% (3/42), reported that the "Filtering Sound Pressure Data" exercise was difficult and too long. This assignment was

Table 6: Categories for the Question "What was your least favorite lab assignment and why?" in Spring Term

Category (Lab Description / Reasoning)	Sample Response	Count
PD Control of an Automotive Suspension When Traversing a Frost Heave / Too Long and Simulation Only	"Week 8 lab was my least favorite lab. It was long and completing the lab in the appropriate time given was difficult and stressful."	15
MATLAB and Simulink Basics / Tedious Compared to Hands-On Exercises	"My least favorite lab was probably our break week where we instead did an Onramp through Mathworks. I think I enjoyed doing activities with Raspberry Pi's too much."	11
Controlling a DC Motor With Raspberry Pi / Wi-Fi Network Connectivity and Hardware Issues	"So far I have not disliked any specific lab. The only thing that has been a little frustrating is sometimes there would be connection issues between the computer and Raspberry Pi that would not allow us to finish the lab but our code would be correct and there was some odd error from the wireless connection issues. I think the lab would be much more effective if the communication method was a hard wire connection."	6
None of the Labs / Most Were Acceptable	"I'm not sure I had a least favorite lab assignment. We learn a lot in each lab and are challenged to recall information or use our cognitive thinking to create solutions we haven't been "directly" taught."	5
Filtering Sound Pressure Data / Difficulty With Filtering Process	"audio signal analysis (week3?) - I struggled a lot with this lab, and it took me all three lab sessions in order to get it to work. The concept had seemed straightforward, but I was very confused the whole time."	3
Reverse Engineering of the Lovebox / Not Well Suited to Group Work	"Some of the group labs were not so good. This was because the person running the raspberry pi had to do very little work compared to the person running matlab and documenting the lab. For me personally when I was running matlab my partner was just kinda sitting there doing nothing while I struggled through (some parts not all) the matlab portion. We switched for one week and that specific week I knew what to do and could've been done in about 30 minutes. My partner struggled through the matlab portion for 2 hours. I tried giving my input and what not but input was not taken effectively. Just gets frustrating. This is more of a who is your partner problem but I wouldn't mind as much if I could've just sat there and worked on something."	2
	TOTAL	**42**

very similar to the “Filtering Engine Mount Acceleration Data” in Winter term, except in that previous course the data to be filtered was provided to the students by the instructors, whereas in the revised course the data was measured by the students themselves. In both versions of the assignment, however, a few students found the filtering task too difficult to complete without significant help. This assignment should be revised to be shorter, or supplementary instruction should be provided to aid students in its completion.

Some students, 14% (6/42), reported that the “Controlling a DC Motor With Raspberry Pi” exercise was their least favorite. This was for the specific reason that there were hardware and infrastructure issues associated with deploying a totally revised laboratory course in just one school term. These students mentioned that the unreliable institutional Wi-Fi network presented roadblocks to coding the Raspberry Pi boards with MATLAB Online and Simulink Online. They were correct in observing that there was a steep learning curve for both students and instructors in employing so many new ideas in just one school term.

Only a few students, 5% (2/42), reported that the “Reverse Engineering of the Lovebox” exercise was their least favorite. This was the last laboratory assignment in the course, and it was generally well received. However, a couple of students picked up on an inherent downside to the redesigned course, which was the group work concept. Due to the number of hardware kits that could be purchased, with some having to be held back for spare parts, students had to work in the laboratory in pairs. In some cases this led to one student in the pair waiting for the other student to complete a task. In the future, this downside could be alleviated to some extent by direct instruction about how to efficiently perform laboratory work in teams. There are “bugs” to be worked out of the revised course, clearly, but at least the students were somewhat indulgent. As one wrote in their survey, “no one expects everything to always run smoothly”.

6 Conclusions and Recommendations

The results of this work demonstrate that low cost physical laboratory experiments can be used effectively in the MECH-431, Dynamic Systems with Controls Laboratory course at KU. In the future, the revised course that employs hands-on experiences will be used instead of the previous course that employed simulation assignments exclusively. The use of Raspberry Pi hardware kits in the revised course has facilitated a reverse engineering exercise involving the Lovebox, a commercially available messaging system. Moreover, the versatility of the Raspberry Pi compute platform will permit other exercises in coding and controls, both for reverse engineering tasks and otherwise. This flexibility will enable different practical applications to be investigated in the laboratory, and thus minimize the likelihood of student academic dishonesty by copying assignments from previous school terms.

Future work should investigate the possible effect that hands-on exercises may have on male / female student diversity in the undergraduate ME program at KU. As published research has shown, female students may have a preference for physical experimentation. But can this preference be confirmed, and if so, what should change in the ME curriculum to accommodate this preference? Could recognition of this inclination ultimately lead to expanded female enrollment in ME undergraduate programs? The answers to these questions are important, as they have the potential to increase the participation of women in engineering.

7 Acknowledgment

The authors would like to gratefully acknowledge the support of the Center for Excellence in Teaching & Learning (CETL) at KU for awarding us with a 2022 CETL Terrell Teaching Innovation Grant. In particular, we would like to thank the CETL Director, Cindy Donner, and the CETL Advisory Board for their monetary and moral support. The Terrell Grant allowed us to purchase the first round of Raspberry Pi kits. We would also like to thank Dr. Bassem Ramadan, Department Head of Mechanical Engineering at KU, for helping us to acquire more Raspberry Pi kits and for funding the acquisition of new desktop workstations in the Denso Lab. Finally, we would like to recognize the helpful contributions of Gen Sasaki, Principal Customer Success Engineer at MathWorks, in providing MATLAB Online and Simulink Online support of the Raspberry Pi compute platform.

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Appendix A

Detail about two new MECH-431 laboratory exercises at KU is provided here.

7.1 Sound Pressure Measurement Exercise – Detail

The new MECH-431 laboratory assignment about the measurement, analysis, and filtering of sound pressure data was developed for the HEAD acoustics Lab, with the following itemized features. The new assignment was designed to take place over two laboratory class periods. The first class is used to acquire, check, and export the sound pressure data, and the second class is used to analyze and filter the data.

- Physical sound pressure is measured for a system that produces readily audible sound.
- Sound sources to be recorded must consist of commonly available items that are owned by the ME department or its instructors, such as hair dryers, hand tools, musical instruments, and automobiles.
- Ambient sound sources such as bird song and vehicular traffic on city streets may also be recorded, weather permitting.
- Only one sound source is recorded each school term, with significantly varying frequency content from source-to-source.
- Students employ the HEAD acoustics ArtemiS SUITE software for data checking, and they export the data in common formats for post-processing in MATLAB and Simulink.
- Students are expected to analyze their sound signals in the time and frequency domains.
- Students are required to identify significant features in frequency domain representations, such as natural frequencies, and calculate damping ratios using the half-power bandwidth.
- Students are tasked with filtering the measured data.
- Filters are designed by students and represented with Bode plots.
- Filtering tasks change each school term depending on the measured sound source.
- While groups of six students acquire and share one set of recorded sound pressure data, each individual student performs their own signal processing tasks.

7.2 Reverse Engineering Exercise – Detail

The new MECH-431 laboratory assignment about reverse engineering of the Lovebox was developed for the Denso Lab. The lab has the following itemized features.

- The functionality of the Lovebox is reproduced using the Raspberry Pi and its accessories.
- The 3D printed shaft attachment will initially be the bulldog shape; however, many different attachments can be created and used each subsequent school term causing different control outcomes.
- Students are expected to use Simulink to control the DC motor to rotate only when a message is incoming and only for a specified number of rotations.
- Students are tasked with programming the Raspberry Pi to display incoming messages on the LCD screen.
- Students are required to measure Bulldog Box system responses, and export the data to MATLAB to see if their design meets the requirements given by the instructor.