Paper ID #40549

Developing an Affordable Multi-Course Electronics Kit for Increased Software and Mechatronic Literacy in Mechanical Engineering

Zhiqing Lu
Herschel Pangborn
Prof. Katie Fitzsimons

Work in Progress: Developing an Affordable Multi-Course Electronics Kit for Increased Software and Mechatronic Literacy in Mechanical Engineering

Abstract

Several Mechanical Engineering (ME) faculty at Pennsylvania State University used course-specific microcontroller-based hardware kits to provide students with hands-on lab experience during the transition to virtual learning in 2020. After returning to on-campus activities, these kits continued to be used to enable open-ended group projects, hands-on homework assignments, and pre-laboratory exercises. We developed an affordable multi-course electronics kit by condensing three current hardware kits in the Circuit Analysis, Mechatronics, and Design Methodology courses. By removing redundant components and replacing expensive parts with cheaper alternatives, we reduced the cost of the condensed kit by approximately 30% compared to purchasing the three course-specific kits. To support the kit usage, we created an online repository with electronic safety, microcontroller tutorials, basic hardware and software instruction, and coding examples. We developed a pre-semester and post-semester survey to assess the impact of the use of an electronics kit on Mechanical Engineering students' basic electronics and programming skills and their engineering self-efficacy in two courses each with enrollments between 150 and 180 students per semester. Our preliminary results show that students' confidence in microcontroller usage, circuit prototyping, and coding increases both for students using the kits for the first time and with use in a subsequent course.

Introduction

When the transition to virtual learning in 2020 prevented traditional hands-on labs, several Mechanical Engineering (ME) faculty in at Pennsylvania State University created course-specific hardware kits that students purchased to perform labs from home. The centerpiece of these kits is an Arduino microcontroller that can be used to collect and analyze data from various electrical, mechanical, and thermal sensors. These kits were required in lieu of textbooks, resulting in a decrease in costs for most students. This pandemic induced transition was generally well-received by students [1] and subsequently featured in a case study [2] and YouTube show [3] created by Arduino Education.

Since returning to on-campus activities, the Arduino platform and several supplemental hardware kits have continued to be used across three required ME courses, where they enable open-ended group projects, hands-on homework assignments, and pre-laboratory exercises. To alleviate logistical challenges of multiple kits and reduce costs, a single kit was developed to be purchased by students upon entering the ME major, with all the components needed for subsequent required courses. Meanwhile, an online repository with sample code, descriptions of components, and tutorials was compiled [4]. This online repository can enable cross-curricular learning, allowing students to link knowledge from different courses. Faculty teaching ME courses can use these sources as supplements for their teaching material—easily implementing hands-on assignments that reinforce theoretical concepts in the course. We formally assessed the use of these kits and online repository using a pre-post semester survey of students. To capture how the kits impact student learning objectives across the curriculum, surveys were administered to both students using the kit for the first time and students with experience from a prior course.

Microcontroller-based kits have been used for a variety of applications in engineering education [5]–[12]. In some cases, low-cost kits were developed to promote engagement in STEM for high school students [5]. Others have studied how a microcontroller-based kit that enabled students to work without the temporal and geographic constraints of bench-top tools improved the academic performance of undergraduate students compared to their counterparts accessing typical lab equipment [6]. Implementations in individual courses have been especially effective in mechatronics courses [7], [13] and introductory engineering courses [8], [9], [14], [15]. Student feedback shows that using kits increase students' learning motivation [16] and understanding of concepts [14]. While individual electronics kits are often used in electrical and computer engineering curricula and the number of low-cost platforms available has continued to increase [17], [18], there are relatively few instances in the literature where microcontrollers have been systematically implemented and assessed across multiple courses in mechanical engineering [16]. In this paper, we focus on how repeated use of a multi-course hardware kit across the ME curriculum improves students' understanding of how theoretical concepts can be put into practical application using basic electronics and programming skills, as well as how this affects their confidence in their ability to write programs and prototype designs. In addition, we explain how key components of the kit were streamlined to reduce cost to the students across three required courses.

The following is a detailed description of the hardware kit development process, online repository design, and an assessment to evaluate efficacy of the hardware kits and online resource in meeting student learning outcomes.

Courses and Course-Specific Hardware Requirements

Penn State's Mechanical Engineering curriculum includes three required courses that have been using Arduino-based kits in lieu of textbooks: (1) Circuit Analysis, Instrumentation, and Statistics, (2) Mechatronics, and (3) Mechanical Engineering Design Methodology since at least Fall 2020.

The Circuit Analysis course serves as an introduction to the fundamental principles of circuit analysis, instrumentation and measurement, as well as statistics. For many students this is the first time they get hands-on experience with electronics and measurement equipment, such as oscilloscopes, breadboards, function generators, and electronic sensors. Prior to the single course kit, students purchased the Arduino Student Kit [19] and a 3-axis accelerometer. Students used the Arduino and the accelerometer to explore concepts like frequency analysis, measurement statistics, and sensor calibration.

The Mechatronics course covers interfacing of electro-mechanical hardware to microcomputers and microcontrollers for data acquisition, data analysis, and digital control. The course addresses the need for today's mechanical engineer to understand the architecture of complex engineering systems and the interface between electronics and mechanical systems. Students used the Arduino—the same one purchased for the circuit analysis course—and purchased a supplemental kit containing a DC motor with an encoder, an infrared distance sensor, power supply, and additional small electronic components such as LEDs and logic gates. In the lab portion of the class, students apply the concepts from lecture by combining the kit's sensors with robotic platforms provided in the lab or with the actuators available in the kit.

Finally, in the third-year Design Methodology course, students are introduced to the engineering design concepts that they apply to an open-ended design problem over the course of the entire semester. The Arduino is often used to enable projects that require actuation and sensing. Past projects have often culminated in a class competition (e.g., a line-follower robot race or "Sumobot" tournament) To build the project, students reused the Arduino Student Kit from the Circuit Analysis course or purchased the kit in advance of taking the Circuit Analysis course. As with Mechatronics, students purchased a supplemental kit specific to the design course including a motor driver shield, DC motors, additional breadboard, and additional power supply.

Development of Multi-Course Hardware Kit

To evaluate candidate components' ability to support the learning objectives of all three courses, the alternatives were tested in all relevant lab procedures and lab instructions were modified to accommodate subtle differences between the new and old components. For example, a class activity involving reading encoder values from the DC motor required students to turn the motor shaft by hand. The lower cost motor had a higher gear ratio that made this more difficult. However, using part of the mounting based from the Arduino Student kit as a wrench or using some other material to increase the effective diameter of the shaft enabled students to overcome this additional motor resistance.

With this verification and slight modifications to lab instructions, instructors from each course provided additional feedback on the lower-cost components. Table shows all components in the final kit. Comparing with the existing kits, we reduce the modified kit cost about 30% (a reduction of approximately $70USD), and the consolidation reduced the shipping cost by two-thirds.

Assessment

To assess the impact of cross-curricular use of an electronics kit on Mechanical Engineering students. We developed a 6-point Likert Scale pre and post survey based on measures developed by Mamaril et al [20] to evaluate students' self-efficacy in prototyping, coding, and engineering skills. The complete pre and post surveys are in Appendix 3 and 4, respectively. The collected data is treated as ordinal data, and a Wilcoxon signed rank test is used to analyze paired data. The correlation between students' reported use of the online resources and their self-efficacy was also evaluated. For this analysis, we use Spearman's rank-order correlation to find the relationship between reported utilization of the website and changes in the students' self-efficacy between the pre- and post-semester surveys. This coefficient should reflect the strength and direction of association between online resource usage and self-efficacy level.

Table 1: Components in Multi-Course Electronics Kit and their use in required courses

Components	**Qty**	**Circuit Analysis**	**Mechatronics**	**Design Methodology**
Decoupling Capacitors	3		●	
DC Barrel Jack Adapter	1		●	●
Jumper Wires (F/F, 20 pack)	6		●	●
Jumper Wires (M/M, 2 pack)	1		●	●
Transistors TIP122G	1		●	
XOR Gate SN74AHC86N	1		●	
Infrared Sensor Wire	1		●	
Infrared Proximity Sensor	1		●	
Mini Photocell	1		●	
NAND Gate SN74S00N	1		●	
Hobby Motor with Encoder	1		●	
AND Gate SN74LS08N	1		●	
Dual TB6612FNG H-Bridge Driver	1			●
Battery Holder With Plug	1		●	●
Adhesive Breadboard	1			●
ADXL335 Accelerometer	1	●		
Arduino Student Kit	1	●	●	●
Protoboard	1	●		

Students enrolled in the Circuit Analysis, Instrumentation, and Statistics course and the Mechatronics course in Fall 2022 were asked to participate in the study. The two courses represent students using the Arduino-based kit for the first time in the mechanical engineering curricula and students using the Arduino-based kit for the second or third time. All participants completed the pre-semester survey in the first two weeks of the Fall 2022 semester and the post-semester survey during the last week of class and finals week. We received 135 pre-semester survey responses and 125 post-semester survey responses from the Circuit Analysis course (Total Enrollment: 188) and 75 pre-semester survey responses and 118 post-semester survey responses from the Mechatronics course (Total Enrollment: 209). After eliminating participants that did not take both surveys, there were 95 paired survey responses from the first-time user group (Circuit Analysis course) and 58 paired survey responses from the experienced user group (Mechatronics course).

Preliminary Results

In the survey students reported their level of agreement to 19 statements related to their experimental, problem solving, prototyping and coding skills. The subset of these statements in which their were significant difference between the pre-semester and post-semester response are shown in Table 2. Students utilizing the kits for the first time rated themselves significantly higher in their ability to work with prototypes, manipulate components, and solve programming issues in their post-semester surveys compared to their pre-semester responses. Students with prior experience using an Arduino-based kit in one or more course also reported more modest but significant increases in their abilities to prototype and program. This suggests that students' self-efficacy in key engineering skills continues to benefit from the hands-on learning facilitated by the multi-course kit. A complete listing of results of the Wilcoxon signed rank test is shown in Appendix 1.

Table 2: Selected Results from the Wilcoxon signed rank test for first-time kit users (Circuit Analysis) and users with prior experience (Mechatronics).

Survey Question	**First-time Users**			**Users with Prior Experience**		
	Pre-	Post-	p-value	Pre-	Post-	p-value
I can write computer programs using simple structure and logic (e.g., if & else statements).	3.79	3.90	0.417	4.05	4.39	0.022
I can use a breadboard to prototype simple electrical circuits.	2.74	4.61	1.867×10^{-14}	4.00	4.60	2.793×10^{-4}
I can program a microcontroller and construct a circuit to complete a useful task	2.19	3.45	7.639×10^{-11}	3.37	4.02	1.248×10^{-4}
I can communicate results of experiments in written form.	4.55	4.76	0.049	4.61	4.75	0.205
I can solve problems using a computer.	4.21	4.68	2.869×10^{-5}	4.54	4.74	0.101
I can build machines.	3.77	4.18	0.0069	3.82	4.26	0.014
I can manipulate components and devices.	3.97	4.42	1.810×10^{-4}	4.18	4.39	0.263

We used the Spearman's rank-order correlation to assess the relationship between student's rating of their skills and their reported used of the online resources developed for the multi-course kit. Not all participants used the resources available on the website, so we conducted this analysis over the entire data set and over the 86 students who reported using the web resources. Questions from the survey with significant correlations to the website use are shown in Table 5. We found that website usage had a negative correlation with analyzing data, oral communication, and working with tools to build/fix things. As a result, we plan to expand the content on the website to support these topics. The main purpose of the website is to support the multi-course kit across the

Table 3: Results of Spearman's Rank Order Correlation with Self-Reported Usage of Online Resource.

Survey Question	**Correlation**	**p-value**
I can analyze data resulting from experiments.	-0.2676	0.0151
I can orally communicate results of experiments.	-0.2438	0.0263
I can work with tools and use them to build things.	-0.2549	0.0200
I can work with tools and use them to fix things.	-0.2531	0.0210

mechanical engineering curriculum, so we plan to continue to collect this type of data to tailor the additional resources to areas that are not directly targeted in course objectives. All results of the Spearman's rank-order correlation are shown in Appendix 2

Conclusion and future work

In this paper, we present an affordable multi-course electronics kit created by merging existing course-specific kits. We reduce the overall cost by removing redundant components and use low-cost alternatives to expensive components—reducing the cost by approximately 30%. We conducted a pre-post survey to assess the impact of cross-curricular use of an electronics kit on Mechanical Engineering students. Our early stage results shows that students' self-efficacy in using microcontrollers, circuit prototyping and coding increased significantly.

References

[1] E. C. Hendrick, "New undergraduate engineering lab successfully stays 'hands-on' during pandemic," 2021. [Online]. Available: https://news.engr.psu.edu/2021/pangborn-herschel-new-undergrad-engineering-lab.aspx

[2] "How to get hands-on while learning remotely: the arduino student kit." [Online]. Available: https://drive.google.com/file/d/1iy4f2b6EhiEPEiOafAArVcs1aZPkusYh/view

[3] Arduino, "Eduvision s3, ep.03: Crack our morse code!" 2021. [Online]. Available: https://www.youtube.com/watch?v=jkpHdQkgvc8

[4] Z. Lu and K. Fitzsimons, 2022. [Online]. Available: https://sites.psu.edu/mehardwarekit/

[5] R. T. Shankar, J. Lapaix, C. P. Weinthal, D. Ploger, M. Augustin, and S. Aguerrevere, "Precision low-cost robotics for math education (work in progress)," in *2015 ASEE Annual Conference & Exposition*, 2015, pp. 26–1242.

[6] J. Yao, L. Limberis, and S. Warren, "Using portable electronics experiment kits for electronics courses in a general engineering program," in *2011 ASEE Annual Conference & Exposition*, 2011, pp. 22–1630.

[7] "Curriculum, equipment and student project outcomes for mechatronics education in the core mechanical engineering program at kettering university," *Mechatronics*, vol. 12, no. 2, pp. 343–356, 2002, mechatronics Education in Europe and the United States.

[8] G. Recktenwald and D. Hall, "Using arduino as a platform for programming, design and measurement in a freshman engineering course," in *2011 ASEE Annual Conference & Exposition*, 06 2011, pp. 22.1609.1–22.1609.23.

[9] D. Geddis, B. Aufderheide, and H. Colquhoun, "Work in progress: Project and design-based introductory engineering course using arduino kits," in *ASEE Annual Conference*, 2020.

[10] G. Heo, "Arduino-compatible modular kit design and implementation for programming education," *Adv. Sci. Technol. Eng. Syst. J*, vol. 5, no. 5, pp. 295–301, 2020.

[11] B. Bajracharya, V. Gondi, and D. Hua, "Iot education using learning kits of iot devices." *Information Systems Education Journal*, vol. 19, no. 6, pp. 40–44, 2021.

[12] S. Glazov, A. Es'Kin, and V. Usol'Tsev, "Using the arduino platform to organize project activities in technoparks," in *2022 2nd International Conference on Technology Enhanced Learning in Higher Education (TELE)*. IEEE, 2022, pp. 27–30.

[13] S. Chehade and A. Smaili, "Effective integration of mechatronics into the mechanical engineering curriculum: A cooperative, project-based learning model with seamless lab/lecture implementation," *International Journal of Engineering Education*, vol. 21, pp. 739–744, 05 2021.

[14] J. Riofrio and S. Northrup, "Teaching undergraduate introductory course to mechatronics in the mechanical engineering curriculum using arduino," in *2013 ASEE Annual Conference & Exposition*, 06 2013, pp. 23.1154.1–23.1154.14.

[15] D. Belfadel, M. Rodriguez, M. Zabinski, and R. Munden, "Use of the arduino platform in fundamentals of engineering," in *2019 ASEE Annual Conference & Exposition*, 06 2019.

[16] L. Funke, J. B. Hylton, and D. Sawyers, "Work in progress: Incorporating microprocessors across the mechanical engineering curriculum," in *2019 ASEE Annual Conference & Exposition*, no. 10.18260/1-2–33630. Tampa, Florida: ASEE Conferences, June 2019, https://strategy.asee.org/33630.

[17] P. Jamieson and J. Herdtner, "More missing the boat — arduino, raspberry pi, and small prototyping boards and engineering education needs them," in *2015 IEEE Frontiers in Education Conference (FIE)*, 2015, pp. 1–6.

[18] C. G. Sawatzki and R. Muraleedharan, "Work in progress: Using cost-effective educational robotics kits in engineering education," in *2021 ASEE Virtual Annual Conference Content Access*, 2021.

[19] Arduino, "Arduino student kit," 2021. [Online]. Available: https://store-usa.arduino.cc/products/arduino-student-kit?selectedStore=us

[20] N. A. Mamaril, E. L. Usher, C. R. Li, D. R. Economy, and M. S. Kennedy, “Measuring undergraduate students’ engineering self-efficacy: A validation study,” *Journal of Engineering Education*, vol. 105, no. 2, pp. 366–395, 2016.

1 Wilcoxon signed rank test Result

Table 4: Complete Results from the Wilcoxon signed rank test for first-time kit users (Circuit Analysis) and users with prior experience (Mechatronics).

Survey Question	First-time Users			Users with Prior Experience		
	Pre-	Post-	p-value	Pre-	Post-	p-value
I can write computer programs using simple structure and logic (e.g., if & else statements).	3.79	3.90	0.417	4.05	4.39	0.022
I can use a breadboard to prototype simple electrical circuits.	2.74	4.61	1.867×10^{-14}	4.00	4.60	2.793×10^{-4}
I can program a microcontroller and construct a circuit to complete a useful task	2.19	3.45	7.639×10^{-11}	3.37	4.02	1.248×10^{-4}
The price of the kit is reasonable.	2.36	2.20	0.077	2.60	2.61	0.969
I can perform experiments independently.	4.30	4.44	0.121	4.40	4.37	0.861
I can analyze data resulting from experiments.	4.63	4.64	0.589	4.68	4.67	0.949
I can orally communicate results of experiments.	4.59	4.77	0.080	4.75	4.74	0.814
I can communicate results of experiments in written form.	4.55	4.76	0.049	4.61	4.75	0.205
I can solve problems using a computer.	4.21	4.68	2.869×10^{-5}	4.54	4.74	0.101
I can work with tools and use them to build things.	4.98	5.03	0.494	4.93	4.93	0.979
I can work with tools and use them to fix things.	4.99	4.92	0.333	4.88	4.90	0.917
I can work with machines.	4.75	4.78	0.543	4.72	24.88	0.240
I can build machines.	3.77	4.18	0.0069	3.82	4.26	0.014
I can fix machines.	3.97	4.16	0.151	4.05	4.20	0.141
I can manipulate components and devices.	3.97	4.42	1.810×10^{-4}	4.18	4.39	0.263
I can assemble things.	5.13	5.03	0.214	5.10	4.88	0.067
I can disassemble things.	5.23	5.15	0.494	5.16	5.09	0.613
I can apply technical concepts in engineering.	4.76	4.86	0.053	4.86	4.79	0.214

2 Spearman's rank-order correlation results

Table 5: Complete Results of Spearman's Rank Order Correlation with Self-Reported Usage of Online Resource. Results are only reported for the 86 participants who reported accessing the website at least once.

Survey Question	Correlation	p-value
I can write computer programs using simple structure and logic (e.g., if & else statements).	0.108	0.323
I can use a breadboard to prototype simple electrical circuits.	-0.140	0.206
I can program a microcontroller and construct a circuit to complete a useful task.	-0.049	0.657
I enjoy using the ETM kit and the online repository	0.078	0.477
The price of the kit is reasonable	0.085	0.439
I can perform experiments independently.	-0.191	0.084
I can analyze data resulting from experiments.	-0.2676	0.0151
I can orally communicate results of experiments.	-0.2438	0.0263
I can communicate results of experiments in written form.	-0.189	0.088
I can solve problems using a computer.	-0.094	0.398
I can work with tools and use them to build things.	-0.2549	0.0200
I can work with tools and use them to fix things.	-0.2531	0.0210
I can work with machines.	-0.072	0.517
I can build machines.	-0.059	0.595
I can fix machines.	-0.061	0.582
I can manipulate components and devices.	-0.090	0.417
I can assemble things.	-0.192	0.081
I can disassemble things.	-0.081	0.467
I can apply technical concepts in engineering.	-0.103	0.353

3 Pre-semester survey

Pre Survey

Please select the class that you are enrolled in for the Fall 2022 semester:	◯Circuit Analysis		◯Mechatronics		◯None of the above
Rate your level of experience with the following:	No experience		Some experience		Significant Past Experience
Arduino or other microcontrollers	◯	◯	◯	◯	◯
Writing computer programs (e.g., C/C++/MATLAB or other programming language)	◯	◯	◯	◯	◯

Please describe your past use of the Arduino or other microcontrollers:						
Please describe which programming language you used and how you used it:						
Rate the degree to which you agree with the following statements.	1 (Strongly dis-agree)	2	3	4	5	6 (Strongly Agree)
I can write computer programs using simple structure and logic (e.g., if & else statements).	○	○	○	○	○	○
I can use a breadboard to prototype simple electrical circuits.	○	○	○	○	○	○
I can program a microcontroller and construct a circuit to complete a useful task.	○	○	○	○	○	○
The price of the kit is reasonable.	○	○	○	○	○	○
Please explain your response to the previous statement "The price of the kit is reasonable":						
Rate the degree to which you agree with the following statements.	1 (Strongly dis-agree)	2	3	4	5	6 (Strongly Agree)
I can perform experiments independently.	○	○	○	○	○	○
I can analyze data resulting from experiments.	○	○	○	○	○	○
I can orally communicate results of experiments.	○	○	○	○	○	○
I can communicate results of experiments in written form.	○	○	○	○	○	○
I can solve problems using a computer.	○	○	○	○	○	○
I can work with tools and use them to build things.	○	○	○	○	○	○
I can work with tools and use them to fix things.	○	○	○	○	○	○
I can work with machines.	○	○	○	○	○	○
I can build machines.	○	○	○	○	○	○
I can fix machines.	○	○	○	○	○	○
I can manipulate components and devices.	○	○	○	○	○	○
I can assemble things.	○	○	○	○	○	○
I can disassemble things.	○	○	○	○	○	○
I can apply technical concepts in engineering.	○	○	○	○	○	○
Demographic Information:	Male	Female	Non-binary /third gender	Prefer to self-describe		Prefer not to say

How do you describe yourself?	◯	◯	◯	________	◯

Choose one or more races that you consider yourself to be	◯ White or Caucasian ◯ Black or African American ◯ American Indian / Native American or Alaska Native ◯ Native Hawaiian or Other Pacific Islander ◯ Asian ◯ Other ◯ Prefer not to say
What is your first language?	◯ English ◯ Spanish ◯ French ◯ Russia ◯ Chinese ◯ Other ◯ Prefer not to say

4 Post-Semester survey

Post survey

Please list all classes in which you used the Arduino kit this semester:						
During this semester, how often did you visit the ME Hardware Kit website (https://sites.psu.edu/mehardwarekit/)	Never	Rarely	Some-times	Often	Weekly	
	◯	◯	◯	◯	◯	
Rate the degree to which you agree with the following statements.	1 (Strongly dis-agree)	2	3	4	5	6 (Strongly Agree)
I can write computer programs using simple structure and logic (e.g., if & else statements).	◯	◯	◯	◯	◯	◯
I can use a breadboard to prototype simple electrical circuits.	◯	◯	◯	◯	◯	◯
I can program a microcontroller and construct a circuit to complete a useful task.	◯	◯	◯	◯	◯	◯
I enjoy using the ETM kit and the online repository	◯	◯	◯	◯	◯	◯
The price of the kit is reasonable.	◯	◯	◯	◯	◯	◯
Please explain your response to the previous statement "The price of the kit is reasonable":						
What is your suggestion to improve the kit and online resource?						
Rate the degree to which you agree with the following statements.	1 (Strongly dis-agree)	2	3	4	5	6 (Strongly Agree)
I can perform experiments independently.	◯	◯	◯	◯	◯	◯
I can analyze data resulting from experiments.	◯	◯	◯	◯	◯	◯

I can orally communicate results of experiments.	○	○	○	○	○	○
I can communicate results of experiments in written form.	○	○	○	○	○	○
I can solve problems using a computer.	○	○	○	○	○	○
I can work with tools and use them to build things.	○	○	○	○	○	○
I can work with tools and use them to fix things.	○	○	○	○	○	○
I can work with machines.	○	○	○	○	○	○
I can build machines.	○	○	○	○	○	○
I can fix machines.	○	○	○	○	○	○
I can manipulate components and devices.	○	○	○	○	○	○
I can assemble things.	○	○	○	○	○	○
I can disassemble things.	○	○	○	○	○	○
I can apply technical concepts in engineering.	○	○	○	○	○	○