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Introducing Arduino to Mechatronics Engineering Students via Lab Activities and a Hands-On Signature-Thinking Course Project

Dr. Lei Miao, Middle Tennessee State University

Lei Miao is currently Associate Professor of Mechatronics Engineering at Middle Tennessee State University (MTSU). He received his Ph.D. degree from Boston University, Master's and Bachelor's degrees from Northeastern University of China, in 2006, 2001, and 1998, respectively. From 2006 to 2009, he was with Nortel Networks in Billerica, MA. From 2009 to 2011, he was with the University of Cincinnati. From 2011 to 2014, he was with NuVo Technologies/Legrand North America. From 2014 to 2015, he was with the State University of New York Farmingdale. He joined MTSU in fall 2015 as an assistant professor and was promoted to Associate Professor in 2020. He has had over 15 years R&D experience in system control and optimization, embedded systems, and intelligent transportation systems. He has had over 40 publications in referred conferences and journals.

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Abstract

Digital Circuits Fundamentals is a junior course offered for mechatronics engineering students at Middle Tennessee State University. Traditionally, this course covered number systems, switches, combinational and sequential logic circuits design, and FPGA programming. In recent years, there is a need to introduce microcontrollers to the students in this course. The reason is that our program does not offer a microcontroller course, but microcontrollers are used very often in senior design and could also be used in the course projects of some upper division courses. The efforts of adding Arduino to the curriculum of Digital Circuits Fundamentals started about three years ago. In particular, we have used a low-cost Arduino kit and redesigned two lab assignments to teach students how to use Arduino and how to interface Arduino with digital displays and sensors. A low floor, wide walls, and high ceiling signature-thinking hands-on course project involving Arduino is required. The students may select any project topic that satisfies the following conditions: *(i)* It is either useful or fun and *(ii)* It has to include a digital display and a sensor or a motor. In addition, the project must have a signature-thinking component, i.e., some aspects of the project must be original.

This paper details how the course was redesigned, the newly added lab activities involving Arduino, and the efforts the instructor put in to ensure the success of the course projects. It should help the engineering programs that do not offer a microcontroller course incorporate Arduino into their curriculum. This paper will also showcase several student projects and some of the design. These projects indicate that students' critical-thinking ability and creativity can be greatly increased when given the freedom to develop their own signature-thinking projects.

1. Introduction

Middle Tennessee State University (MTSU) offers an ABET Engineering Accreditation Commission (EAC) accredited mechatronics engineering program, in which students learn both electrical and mechanical engineering course materials. Digital Circuits Fundamentals is one of the required electrical courses in the curriculum, typically taught in the junior year. The prerequisites of this course are Computer Science I and Electrical Circuit Analysis I. It is the prerequisite of two other courses: Programmable Logic Controllers and Networks and Introduction to Feedback Control. Traditionally, Digital Circuits Fundamentals covered number systems, switches, combinational and sequential logic circuits design, and Field Programmable Gate Arrays (FPGA) programming. In recent years, there is a need to introduce microcontrollers to the students in this course. The reason is that our program does not offer a microcontroller course, but microcontrollers are used very often in senior design and could also be used in the course projects of some upper division courses such as Introduction to Feedback Control. The efforts of adding microcontrollers to the curriculum of Digital Circuits Fundamentals started about three years ago. Among a wide range of available microcontrollers, we selected Arduino due to the following reasons: (1) Its hardware design is open-source; (2) Its cost is low; (3) It is extremely popular among both hobbyists and professionals; and (4) There are lots of online resources for Arduino.

In academia, Arduino has been widely adopted for various purposes. In [1], Arduino was used in a summer camp to promote the interests of high school students in STEM. A similar effort was reported in [2] where graduate students and high school teachers teamed up to train high school students using Arduino. Arduino has also been used in first-year engineering courses. Some earlier works that introduced it to freshman engineering students via hands-on activities can be found in [3] and [4]. Daugherity [5] used Arduino to teach freshman students programming and problem solving. Geddis et al. [6] used Arduino kits in a freshman engineering course in which lessons were taught, followed by a 4-week long project. A similar effort was reported in [7] and [8] where several mini lessons were taught in a first-year engineering course to help improve retention. Aspects of Internet of Things such as using Arduino to interface with a Wi-Fi module and access a database were introduced to students in a freshman engineering course [9]. It has been shown in [10] that Arduino could be taught as an online course to freshman engineering students.

Arduino has also been used in sophomore and junior engineering courses. In [11], project-based learning was utilized where 4 Arduino labs were taught, followed by a 2-week long project. Bedillion et al. [12] adopted Arduino hardware platform for a sophomore mechanical engineering design course, in which students were asked to complete two course projects: a small ground robot and an RC toy car, after doing some lab activities. Miao and Li [13] organized a summer research and enrichment program using Arduino to engage minority and underrepresented students. Riofrio and Northrup taught an introduction to mechatronics course using Arduino for mechanical engineering students, and the group project was to build a solenoid engine with emphasis on the mechanical aspects.

Our course revitalization started in Fall 2020. In our revised course, the learning objective related to Arduino is to learn microcontroller hardware interfacing and software programming basics using project-based learning. Compared with existing efforts in the literature, our work differs in the following ways: *(i)* We introduce Arduino to the students without modifying the course curriculum significantly; *(ii)* We allow students to choose their own project topics with a signature-thinking component; and *(iii)* We establish a mechanism to help the students succeed in the project.

The organization of the rest of the paper is as follows: Section 2 discusses the details of the lab assignment changes; Section 3 presents the course project requirements and scheduling; Section 4 showcases several past student projects; Section 5 discusses the outcomes of introducing Arduino; finally, we conclude in Section 6.

2. Changes to the Lab Content

The weekly schedule of Digital Circuits Fundamentals is 2-hour lecture and 3-hour lab. Due to the limited lecture time, we could not cover Arduino during the lecture and decided to introduce it to the students during the lab. Table 1 shows the lab assignments used before and after introducing Arduino.

In the past, we had FPGA and Very High-Speed Integrated Circuit Hardware Description Language (VHDL) covered in four labs (lab #5, 6, 7, and 10), but now we only have lab 5 related to them. The shift in focus allowed us to introduce Arduino to the students in lab 2 and lab 3 and also make some other changes to the lab assignment. For example, counter design used to be done in Lab 9 using JK flip-flops and in Lab 10 using VHDL, but we now ask the students to design ripple and synchronous counters in Lab 8. For the most part, our educational objectives are unchanged, except that we now introduce Arduino and emphasize less on FPGA and VHDL.

Table 1. Lab assignment before and after introducing Arduino

Lab Assignments	Before introducing Arduino	After introducing Arduino
Lab 1	Number Systems	Number Systems
Lab 2	Switches	Digital Signals and Arduino
Lab 3	Basic Logic Gates	Basic Logic Gates and Pulse Width Modulation
Lab 4	Basic Logic Gates and Multisim tool	Basic Logic Gates and Multisim tool
Lab 5	Combinational Logic Design and Introduction to FPGA and VHDL	Combinational Logic Design and Introduction to FPGA and VHDL
Lab 6	7-semgnet Decoder	Two's Complement
Lab 7	Two's Complement	Latches
Lab 8	Latches	Counters
Lab 9	JK Flip-flops	Linear-Feedback Shift Registers
Lab 10	Counter Implementation using VHDL	Project time

The Arduino kit we use is the ELEGOO UNO Project Super Starter Kit, which could be bought from Amazon for around $40. The kits are provided by the department. Students check them out in the beginning of the semester and are required to return them in the end. We selected this kit because it is very cost-effective and has excellent review (4.7 out of 5 on Amazon as of March 2024). The quality of the kit turns out to be outstanding, and we never had any issues with it. It is worth noting that the supplier ELEGOO offers several Arduino kits, including more expensive ones that come with Arduino Mega and more sensors. Nonetheless, the Super Starter Kit we use fits our needs.

As shown in Fig. 1, the kit contains many hardware components which are listed in the Appendix. The kit also comes with lessons and all the corresponding Arduino sketches and .ZIP libraries. Fig. 2 shows the table of content of the lesson file.

2.1 Short Arduino tutorial

Arduino has been very popular among hobbyists and has been used in extracurricular activities at some high schools. However, most of our students fall into at least one of the following categories: minority, underrepresented, first-generation, and nontraditional. As a result, most of them have no experience with Arduino when taking this course. For the small percentage of students who have used Arduino before, their experience is very minimal. Therefore, a tutorial to Arduino is essential for the students to get started.

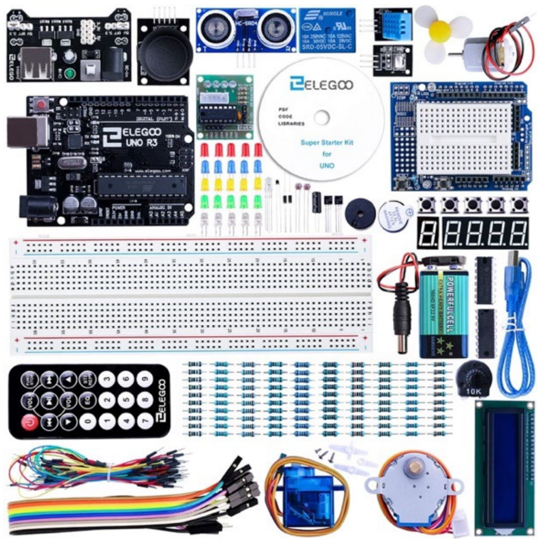

Figure 1. Hardware complements included in the ELEGOO UNO Project Super Starter Kit

Content

Lesson 0 Installing IDE....9
Lesson 1 Add Libraries and Open Serial Monitor....22
Lesson 2 Blink....31
Lesson 3 LED....39
Lesson 4 RGB LED....46
Lesson 5 Digital Inputs....55
Lesson 6 Active buzzer....60
Lesson 7 Passive Buzzer....64
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Lesson 9 Servo....72
Lesson 10 Ultrasonic Sensor Module....76
Lesson 11 DHT11 Temperature and Humidity Sensor....81
Lesson 12 Analog Joystick Module....87
Lesson 13 IR Receiver Module....92
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Lesson 21 DC Motors....136
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Lesson 24 Controlling Stepper Motor With Remote....159

Figure 2. Various lessons included in the ELEGOO UNO Project Super Starter Kit

After lab 1 is completed, we give the students a short tutorial to Arduino. In particular, we show how to use Arduino IDE to write sketches, how to compile and upload the code to Arduino, the purposes of the setup and the loop functions, basics of I/O PINs, etc. We run the blink sample code and demonstrate that the onboard LED attached to digital PIN 13 can flash at different frequencies. We also present how to add a .ZIP library. The short tutorial helps students get started with Arduino programming. One challenge is that some students learned Python, instead of c++, in the prerequisite Computer Science I. This problem has been mitigated by encouraging a student who knows c++ to team up with another student who knows Python.

2.2 Modified lab assignments that involve Arduino

We have two modified lab assignments that have Arduino related activities. In lab 2: Digital Signals and Arduino, we first ask the students to modify the example file "blink" and implement the Morse code of SOS using an LED, a current limiting resistor, and digital PIN12. In part 2 of the lab, we ask the students to read and implement Lesson 7 Passive Buzzer and Lesson 5 Digital Inputs. Then, they are instructed to combine the two lessons and use a push button to control the passive buzzer.

In lab 3: Basic Logic Gates and Pulse Width Modulation, we keep some content of the original lab 3 and add an Arduino related assignment. Specifically, we ask the students to read and implement Lesson 4: RGB LED and Lesson 8: Tilt Ball Switch. Then, they are instructed to combine the two lessons and use the tilt ball switch to control the RGB LED. After lab 2 and lab 3, students learn how to use Arduino to interface with sensors, LEDs, push buttons, etc. They also learn how to use Arduino IDE to program Arduino and troubleshoot issues.

3. Course Project Requirements and Scheduling

Our course has a required course project that counts 15% towards the overall course grade. It is a perfect vehicle for the students to utilize project-based learning to gain more knowledge about Arduino and enhance their critical thinking ability and creativity. The project costs are paid by our department, and each student has a budget of $50.

After lab 3 is completed in week 4 of the semester, the course project is announced in the week after. The project has the following properties:

(1) Low floor, wide walls, and high ceiling. The project only requires knowledge of algebra, basic electric circuits, and Arduino programming. The students may select any project topic that satisfies the following conditions: *(i)* It is either useful or fun and *(ii)* It has to include a digital display and a sensor or a motor. We do not limit the imagination of the students, as long as the project is feasible and can be done within 7 weeks.

(2) Must have a signature-thinking component. There are lots of online resources related to Arduino based projects. On one hand, we encourage students to learn from these existing projects; on the other hand, we require them to have a signature-thinking part in their course projects, i.e., some aspects of the projects must be original. It is required that students must cite the online sources they have used in the project report.

When the project requirements are announced in week 5, we show videos of previous course project demos so that students get a sense of what have been done in the past. Then, they are asked to form project teams (each team usually has two team members) and come up with at least two ideas by the start of week 7. The project ideas count 15% towards the project grade and need to be submitted in writing and include the following components for each project idea: *(i)* title and description; *(ii)* originality statement, i.e., what makes the project different from other ones; *(iii)* Bill of Materials (BOM); and *(iv)* feasibility study (explain why the project is doable and why it can be delivered successfully by the due date).

In week 7, the instructor meets with each project team to discuss their project ideas and help them pick one based on the students' interests, feasibility, originality, and other factors. At the meeting, the instructor also works with the team to finalize the BOM. Because the fall break and spring break typically start in the end of the 7th week, we try to place orders right after the meeting so that the students may possibly get the parts right after the break and start working on the project as early as possible.

The final project demo takes place in the last day of class. Nonetheless, there is a mid-way progress demo which occurs a week prior to the final demo and counts 15% towards the project grade. To get the mid-way progress demo credit, the students need to show that their project is basically working and close to finish. The purposes of the mid-way demo are two-fold: *(i)* It encourages the students to start working on the project early and avoids the last-minute rush and *(ii)* It gives the students a chance to tinker their project after receiving feedback from the instructor.

We have limited lab time allocated for project completion, and the students are supposed to work on the project using their own time after class. Throughout the second half of the semester, the instructor is available to answer questions students may have regarding the project.

4. Sample Course Projects

In this section, we present several course projects completed by students in Digital Circuits Fundamentals.

(1) Portable Luggage Scale with Airline Weight Limit Indication

In this project, the students designed a portable luggage scale. Because luggage scales could be purchased from stores at a low price, the signature-thinking part is to add weight limit indication: *(i)* If the luggage is good for carry-on purposes, then the LED is green; *(ii)* If it is good for check-in, but not carry-on, then the LED is yellow; and *(iii)* If it is not good for either carry-on or check-in, then the LED is red. Fig. 3 shows the finished product and the design.

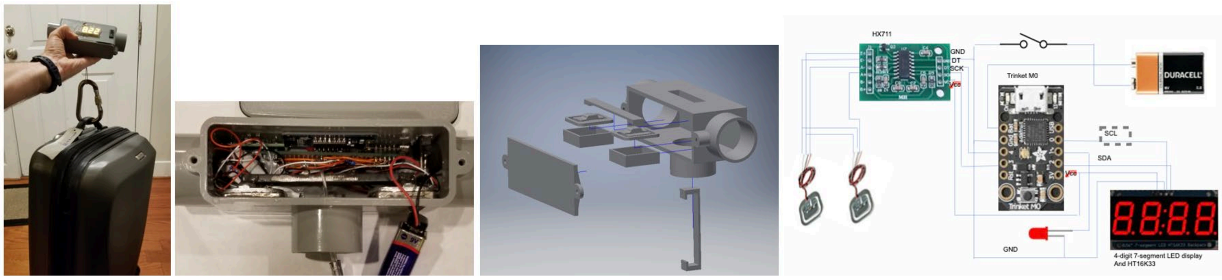

Figure 3. Portable Luggage Scale with Airline Weight Limit Indication

(2) Wireless Moisture Sensing and Alarm System

In this project, the student originally wanted to implement a moisture sensor capable of detecting water leak. Because such a device with audio alarm could be purchased at a low price from home improvement stores, the signature-thinking part is to add a wireless capability: if moisture is detected, it will notify a user at a remote location by turning on an LED. The wireless capability makes the system more valuable in some scenarios. For example, if the user is deafened, then the LED indication will be better than the audio alarm. In another example, if the user is far away from the scene, then she could still be notified. A pair of Zigbee transceivers were used in the project for wireless communications. Fig. 4 shows the finished product.

Figure 4. Wireless Moisture Sensing and Alarm (Left: Transmitter, Right: Receiver)

(3) Skittle Sorter

The basic function of the skittle sorter was to sort skittles by their colors to allow the person eating them to choose their favorite flavor without having to sort through the bag. The project was unique compared to other skittle sorters because of the extra added bin that is designed for all the defective-colored skittles and the fact that it is more compact. Also, its hexagonal shape contributed to the overall originality of the mechanism. Fig. 5 shows the finished product and the design.

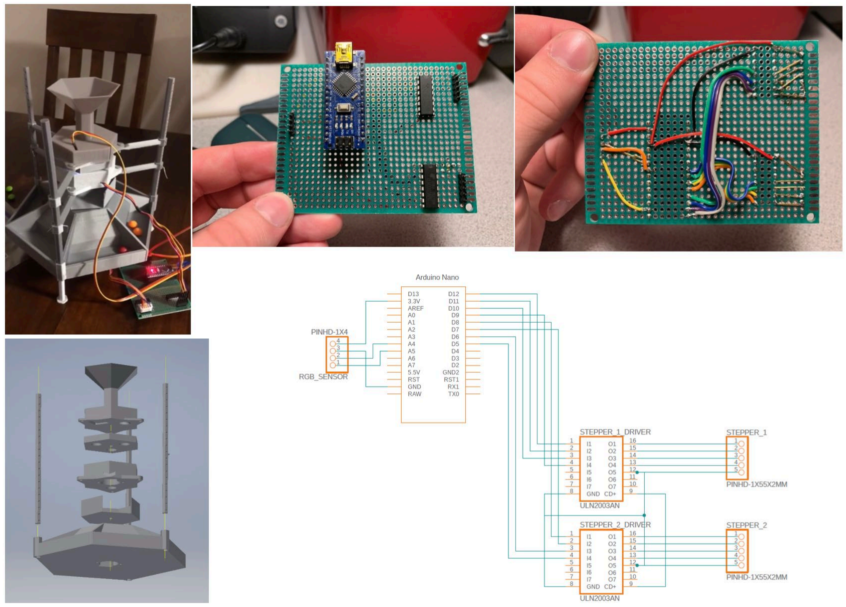

Figure 5. Skittle Sorter

(4) LED Arm-Wrestling Referee

The students designed an arm-wrestling table capable of automatically detecting the presence of players, starting the game, and declaring the winner using audio and colorful LED strings. The signature-thinking part was the different light shows that were given based on the state of the table: idle, one player contact, two player contact, game set, game sequence, and game over. The presence of the players and the winner were detected by the MRP121 capacitive touch sensors which were embedded into the handles and the pads. Fig. 6 shows the finished product and the design.

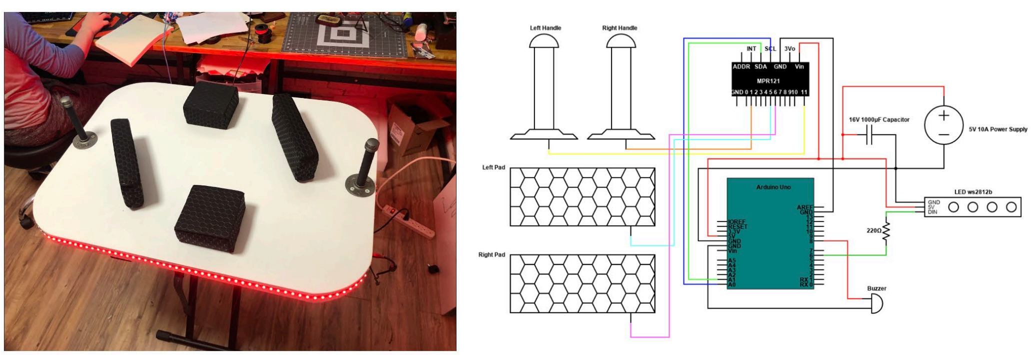

Figure 6. LED Arm-Wrestling Referee

(5) Handy Man

In this project, the students built a robotic hand consisted of 3d printed fingers and palm, fishing lines, servo motors, and rubber bands as tendons. As shown in Fig. 7, it was controlled by a user wearing a glove with flex sensors attached.

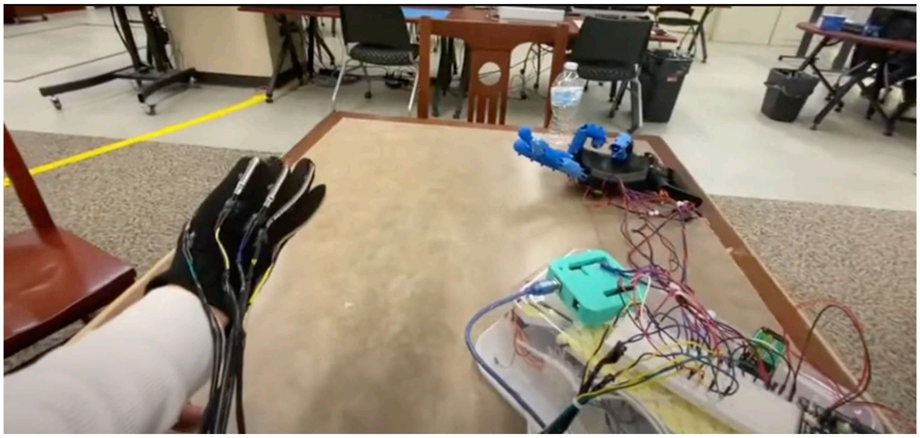

Figure 7. Handy Man

5. Outcomes

Below are selected comments from the student teaching evaluation regarding the project and the lab:

(1) "I liked the format of the course and the cool projects! I'm impressed that not only did he get us Arduinos, he also got us $100 budgets for our project. The teaching style was excellent and the grading was clear and fair with some extra credit offered."
(2) "I loved the project that we were assigned to do. I think it was a great way to have the students apply their knowledge of digital circuits to a real-life application."
(3) "The course was fun, extremely relevant to real world applications"
(4) "I think the labs and project was the strength of this course. I learned the most from these aspects as they were a good challenge to the group."
(5) "Have a more in-depth lecture over the coding of an Arduino as it's very contingent on the success of the class as it's part of the final project and many people may not be experienced in the coding language used for the provided Arduino's"

The students appear to like the Arduino-based lab activities and course projects, although one person complained about not having enough knowledge of the Arduino programming language. Moving forward, we could convert one more lab to Arduino-based in order to strength students' coding ability. In addition, since Arduino can also be controlled using Python, we could let the students program Arduino using either Arduino programming language or Python in the future.

Almost all the students who have taken this course since Spring 2021 utilized Arduino in subsequent courses in the curriculum. For example, they have applied PID control on Arduino in the Introduction to Feedback Control course for several different projects, including line following robot, ball levitator, ball balancer, and inverted pendulum self-balancing robot. Without learning Arduino in Digital Circuits Fundamentals, they would not be able to complete these course projects in just a few weeks. They have also used Arduino in their capstone senior design projects to build line following tennis ball shooter, remote controlled mobile trebuchet, robotic cat, robotic dog, Rubik's cube solving machine, hovercraft, submarine, etc. Prior to learning Arduino in Digital Circuits Fundamentals, students had to learn Arduino themselves while doing capstone senior design. As a result, they often could not build the working prototype until the second semester of the year-long senior design. After learning Arduino in Digital Circuits Fundamentals, the seniors were able to implement the working prototype by the end of the first semester of the capstone senior design, which gave them more time to improve their design in the second semester.

Introducing Arduino to the students may also have slightly improved their performance in the course. From Fall 2017 to Fall 2019, 129 students took the course, and the average course grade percentage was 79.57%. From Spring 2021 to Fall 2023, 125 students took the course, and the average course grade percentage was increased by 3.37% to 82.94%. Since the lecture of the course was unchanged, the lab content modification is likely the reason behind the student performance improvement. Nonetheless, we do not know for sure since the student course grades fluctuate over time due to random factors.

6. Conclusions

In this paper, we have discussed a course revitalization effort in which Arduino is introduced to Mechatronics Engineering students in a Digital Circuits Fundamentals course. We modified the lab content by adding an Arduino tutorial and two lab modules. After learning basics of microcontroller hardware interfacing and programming, students' skills are further sharpened through project-based learning. In our course, a low floor, wide walls, and high ceiling course project is required in which students are free to select their own project topic, as long as it is either useful or fun and has a signature-thinking component. We have used meetings and a mid-way progress demo to help the students determine the topic and meet the deadline.

Our course revitalization efforts have yielded many successful and unique projects, some of which are presented in this paper. Students indicated in the teaching evaluation that they enjoyed the project, and our efforts may also have had a positive impact on the average course grade percentage. After taking the revitalized course, our students have been able to use Arduino in various other course projects and capstone senior design projects. Based on the above outcomes, we consider our efforts a great success. We hope that what we have done in this course can be helpful to other engineering programs such as Mechanical Engineering that currently do not offer a microcontroller course but wish to give their students some exposure to Arduino or other type of microcontrollers.

Appendix

Hardware complements included in the ELEGOO UNO Project Super Starter Kit:

1pcs UNO Controller Board; 1 LCD1602 Module (with pin header); 1 Breadboard Expansion Board; 1 Power Supply Module; 1 Joystick Module; 1pcs IR Receiver; 1 Servo Motor (SG90); 1 Stepper Motor; 1 ULN2003 Stepper Motor Driver Board; 1 Ultrasonic Sensor; 1 DHT11 Temperature and Humidity Module; 1 9V Battery; 65 Jumper Wire; 1 USB Cable; 1 Active Buzzer; 1 Passive Buzzer; 1 Potentiometer; 1 5V Relay; 1 Breadboard; 1 Remote; 1 Tilt Switch; 5 Buttons (small); 1single digit 7-segment Display; 1 4 digit 7-segment Display; 5 Yellow LEDs; 5 Blue LEDs; 5 Green LEDs; 5 Red LEDs; 1 RGB LED; 2 Photo resistors; 1 Thermistor; 2 Diode Rectifiers (1N4007); 2 NPN Transistors (PN2222); 1 IC 74HC595; 120 Resistors; 10 Female-to-male DuPont Wire; 1 DC motor; and 1 Fan blade.

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