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Teaching Electronics Laboratory Classes Remotely

Dr. David RB Kraemer, The Johns Hopkins University

After earning his PhD from Johns Hopkins University, Dr Kraemer has focused his career on undergraduate engineering education. Previously, he taught as a Full Professor of Mechanical Engineering at the University of Wisconsin - Platteville. He is currently an Associate Teaching Professor of Mechanical Engineering at the Johns Hopkins University.

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The global pandemic has made teaching postsecondary laboratory courses particularly difficult. Even at schools where students are in person, the high-contact nature of laboratory instruction means that these courses cannot be taught in their usual fashion. Many recent efforts to continue high-quality education during remote learning have focused on simulations of laboratory experiments [1]. This paper describes the author's methods for adapting two undergraduate engineering laboratory courses for remote instruction: a basic circuits course, and a basic mechatronics course. Both courses rely heavily on the hands-on experience of their laboratory components.

Laboratory experiences, when successful, are the most active of active learning experiences. Much of the literature that studies active learning focuses on improving classroom experiences [2]; this is a natural focus of effort, since traditional lectures can disengage many students. Some studies have focused on laboratory exercises, but these studies have naturally involved in-person exercises in traditional laboratories[3]. Overall, active learning techniques have proven effective [4]. This is a strong reason to preserve and improve on the active laboratory experiences in this time where many learning experiences have become less engaging, overall.

Teaching Electronics Laboratory Classes Pre-Pandemic

Before the recent pandemic forced most classes to be taught remotely, these two electronics-focused courses were taught in the same laboratory facility at my university. Groups of approximately 16 students, working in pairs, used equipment on benches in a traditional teaching laboratory. Permanent equipment at each station included oscilloscopes, function generators, and power supplies (see Figure 1). This equipment, purchased new, would cost in the range of USD$5k to $20k, multiplied by the number of lab benches needed.

Figure 1. Full-size laboratory equipment: oscilloscope, function generator, and variable power supply.

Simulation of Electronic Circuits

In both the basic circuits course and the basic mechatronics course, circuit simulations using the free TinkerCAD web-based simulation tool were used. Numerous electronic simulation tools are available, including the open-source SPICE (Simulation Program with Integrated Circuit Emphasis). For these introductory courses, the author chose TinkerCAD for circuit simulation because of its user-friendly interface and large collection of simulated devices.

In the spring of 2020 university instruction was abruptly interrupted midway and courses were forced to go remote in mid-semester. The second half of the laboratory exercises were adapted to be performed solely with online circuit simulations. This proved to be acceptable because students had hands-on experience with real laboratory equipment during the first half of the course. A completely simulated laboratory experience would not have allowed students to achieve the stated outcomes for the course.

For the fall 2020 and spring 2021 semester, the simulations allowed for experiments to proceed in the first few weeks while equipment kits were sent out to remote students. Once equipment kits allowed experiments with hardware, the simulations proved useful to supplement the experiments for comparison of theory and experiment.

An excerpt from a typical laboratory exercise is shown in Figure 2. The corresponding simulation is shown in Figure 3.

I. Resistor Network: Nodal Analysis

1. Analyze the circuit given in Figure 1 below. Write equations for v_a through v_e in terms of I_1, I_2, and the R's. (Note: one of the voltages will be your reference node. This takes some work; you don't have to do it in the lab period. Write your equations in matrix form. Show your work.)

2. Create the circuit on a breadboard in TinkerCAD. Note that each breadboard hole can only have one wire. Include a screen shot in your report; label resistors $R1$ through $R5$ and nodes a-e on the screen shot.

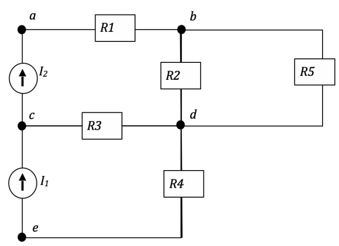

Figure 1. Resistor network.

3. Set R_1 to 1Ω, R_2 to 2Ω, R_3 to 3Ω, R_4 to 4Ω, R_5 to 5Ω, I_1 to 1A and set I_2 to 2A. Measure and record the voltages using multimeters.

4. Compare theory and simulation for the node voltages. Calculate the theoretical voltages by using a numerical solver such as MATLAB.

Figure 2. Excerpt from a typical laboratory exercise from the basic electronics course.

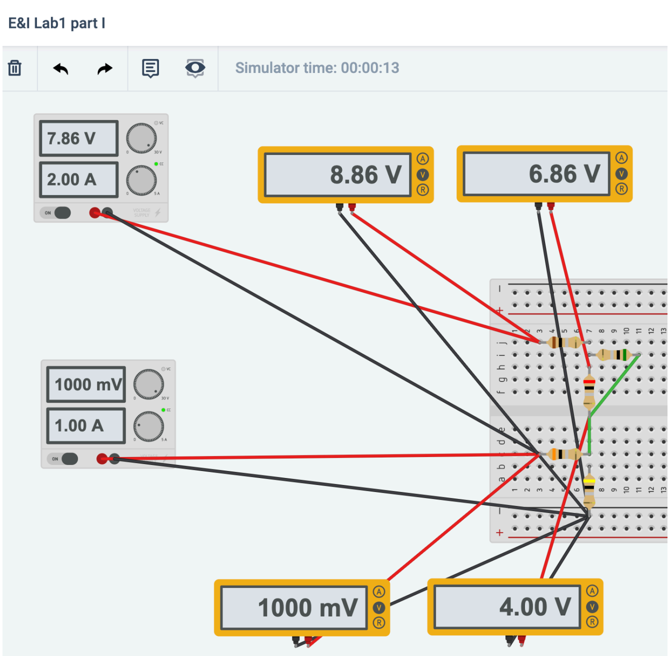

Figure 3. TinkerCAD circuit simulation corresponding to the exercise in Figure 2.

TinkerCAD proved extremely useful for these laboratory courses. However, there were a few limitations: for example, no stepper motors are available for the simulations. More importantly, the oscilloscopes in the simulation can only display a single input signal. Multiple oscilloscopes can be used to display multiple signals, but because they are all independently triggered, it is impossible to see phase relationships between signals. Finally, simulations can make it easy to create circuits that are unreasonable in reality. Figure 3 shows that the resistor values chosen lead to high currents that would burn the resistors rather quickly. It is anticipated that once in-person instruction is fully resumed, simulations will continue to be used as before the pandemic: as a useful tool for students to learn, and a limited supplement to hands-on experimentation.

Electronics Laboratory Kits

Kits of electronic equipment were shipped to remote students and distributed contact-free to local students.

Table 1 shows the list of items purchased for each student in the basic electronics course. Spare parts were included for items that tend to fail; spare fuses were included in the kit, based on experience with frequent blown fuses during measurements of current. Beyond a pre-packaged electronics kit with a breadboard, jumper wires, resistors, capacitors, and LEDs, the kit included inductors, npn bipolar junction transistors, op-amps, and NAND gate integrated circuit chips. The basic electronics class included a series of 10 laboratories and an open-ended project. Projects could be completed with the equipment included in the kit, or a limited amount of other parts could be purchased.

Table 1. Equipment kit purchased for basic electronics course, for each student.

ITEM	Quantity	Approximate Cost each	Total
multimeter	1	$35.99	$35.99
10mH inductors	2	$0.50	$1.00
alligator clip wires	4	$1.00	$4.00
electronics kit (breadboard, resistors, capacitors, jumper wires, LEDs, etc.)	1	$17.98	$17.98
USB oscilloscope/function generator/power supply, Espotek Labrador	1	$29.00	$29.00
Zener diodes	2	$0.60	$1.20
555 timer chips	2	$0.50	$1.00
NAND gates, 7400	2	$0.50	$1.00
9V battery clips	2	$1.00	$2.00
temperature sensor TMP36	1	$1.25	$1.25
op-amp chips, LM324N	2	$0.40	$0.80
fuse, 400mA 600V	2	$3.00	$6.00
USB micro cables	1	$1.50	$1.50
9V batteries	2	$1.50	$3.00
TOTAL approximate cost, USD per student			$105.72

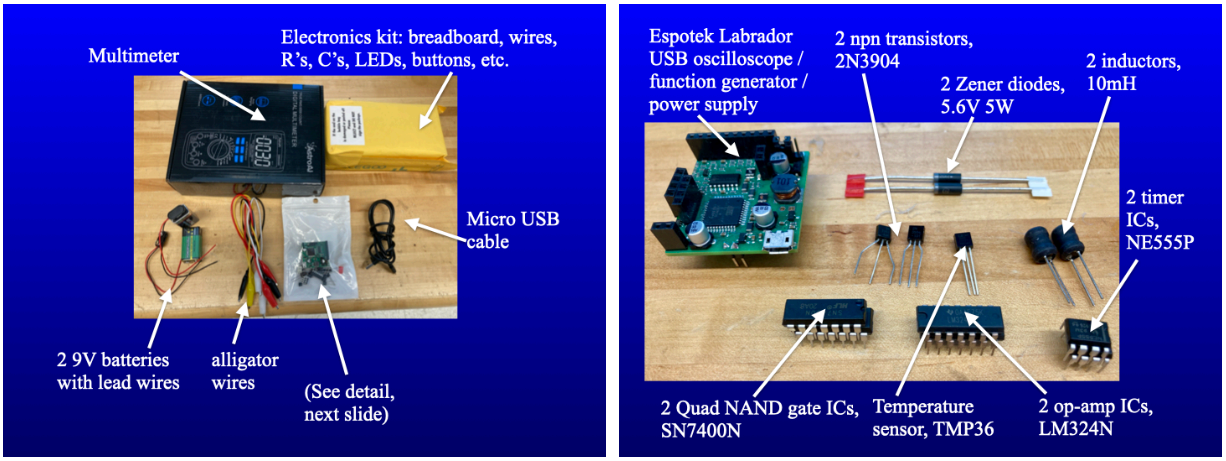

Figure 4. Basic electronics course equipment kit.

Table 2 shows the list of items purchased for each student in the basic mechatronics course. Spare parts were included for items that tend to fail. The class included a series of 10 laboratories and an open-ended project. Projects could be completed with the equipment included in the kit, or a limited amount of other parts could be purchased.

Table 2. Equipment kit for basic mechatronics course, for each student.

ITEM	Quantity	Approximate Cost each	Total
Infrared emitter-sensor EE-SX1042	2	$3.00	$6.00
GPS receiver, NEO-6M	2	$11.99	$23.98
USB oscilloscope/function generator/power supply, Espotek Labrador	1	$29.00	$29.00
USB micro cables	1	$2.00	$2.00
Hall-Effect sensor SS49E	2	$1.00	$2.00
DC motors with encoders, 150 RPM, 34:1 gear ratio	1	$15.99	$15.99
Arduino UNO R3 starter kit (includes ultrasonic sensor, hobby servomotor, stepper motor, breadboard, jumper wires, etc)	1	$36.99	$36.99
Infrared distance sensor, Sharp 2Y0A21	1	$6.00	$6.00
OLED screens 0.96 inch, IIC	1	$6.00	$6.00
Inertial Measurement Unit, MinIMU-9	2	$11.95	$23.90
Darlington transistor arrays, ULN2803A	2	$1.00	$2.00
MOSFET, IRFZ44N	1	$0.50	$0.50
momentary switch buttons	4	$0.50	$2.00
RF transceivers, Adafruit RFM69HCW 900MHz	2	$7.96	$15.92
H-Bridge chips, L293D	2	$1.00	$2.00
10kΩ potentiometer	2	$0.70	$1.40
Male-female jumper wires	10	$0.20	$2.00
Arduino breadboard shields	1	$6.69	$6.69
9V batteries	2	$1.50	$3.00
TOTAL approximate cost, USD per student			$187.37

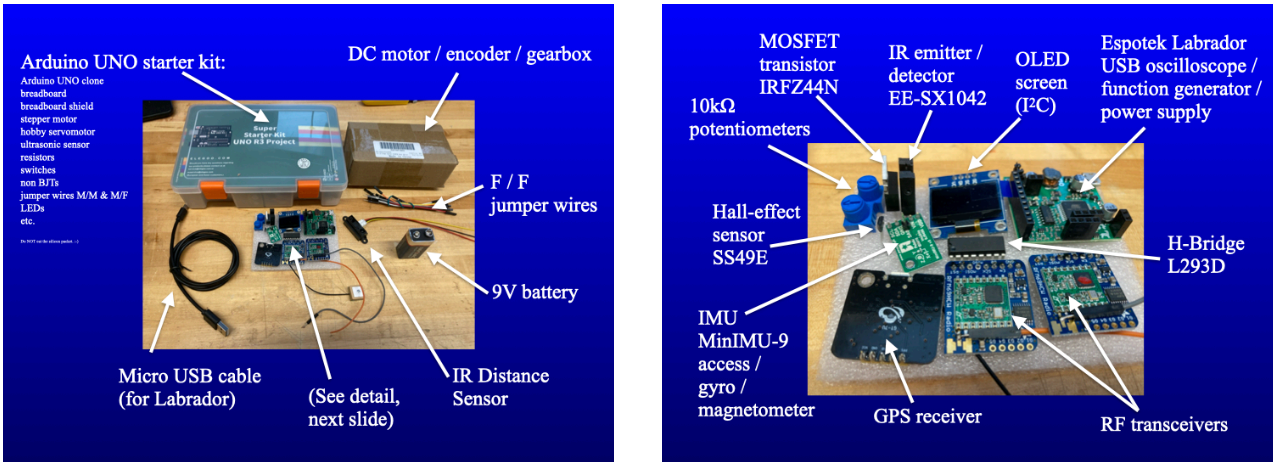

Figure 5. Basic mechatronics course equipment kit.

USB Oscilloscope / Function Generator / Variable Power Supply

One piece of equipment that was pivotal to the remote laboratory experiments was the Espotek Labrador USB oscilloscope / function generator / variable power supply. This device has significant limitations, but at USD$30, it enables assembling kits for non-trivial experiments at a surprisingly affordable cost. This device uses an open-source hardware design, with open-source cross-platform software.

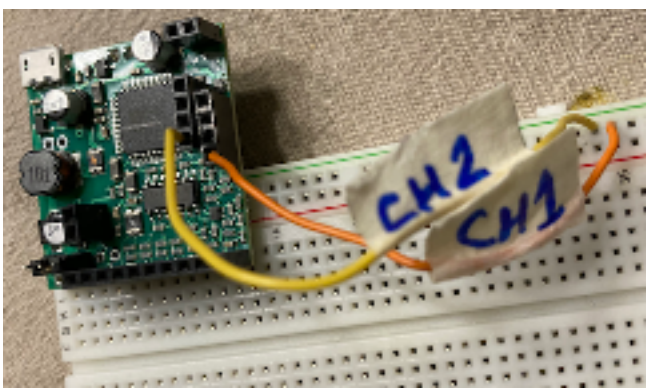

Figure 6. USB Oscilloscope / Function Generator / Variable Power Supply, mounted on a breadboard.

The oscilloscope shows significant noise even on a signal generated by its own generator; see Figure 7. One of the main limitations of the USB oscilloscope is its sampling rate. At 750k samples per second, it is suitable only for displaying signals at about 100kHz and slower. In the basic mechatronics course, a serial signal from a GPS receiver at 9600 baud was easily displayed. Similarly, the USB oscilloscope was useful for displaying the encoder sensor signals from a DC motor/encoder. However, the sample rate limitation prevented the analysis of an SPI serial data signal which had been used in previous semesters, because the clock frequency is 1MHz. Furthermore, the oscilloscope does not have mathematical functions (even simple ones such as finding the difference between two signals), but the data can be easily exported to a spreadsheet for further analysis offline.

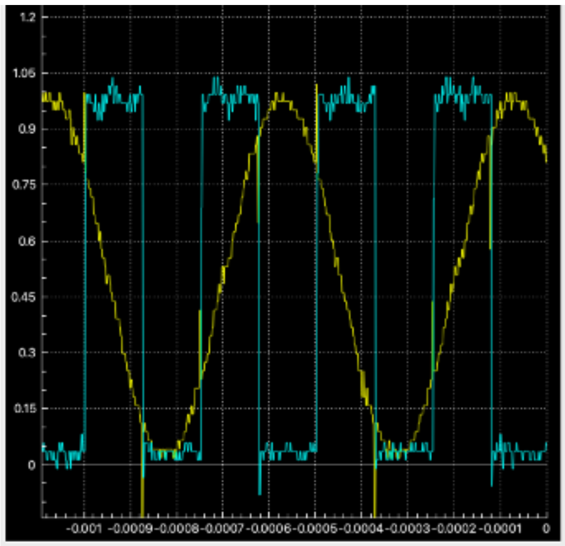

Figure 7. A 2kHz sine wave and a 4kHz square wave generated by the signal generator and displayed on the oscilloscope of the Labrador device.

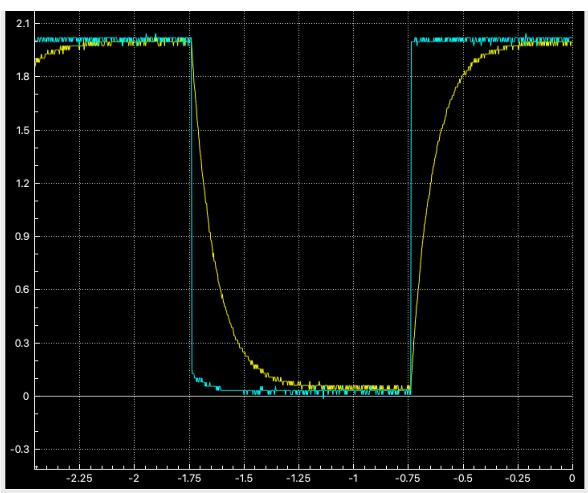

Figure 8. Transient response of an RC circuit: square-wave input signal (blue), and output voltage across the capacitor (yellow).

Figure 8 shows that, even when using a relatively high-impedance load (the RC circuit here has an impedance of 33kΩ), the signal generator's output shows significant deviation from the desired square wave.

Another limitation of the Labrador device is that the signal generator cannot output negative voltages. Furthermore, the variable power supply has a limited in range of 4.5V to 12V.

Conclusions

The courses were well received. Student evaluations indicated positive results; the quality of the course and, importantly, the intellectual challenge of the course were seen to be quite similar to those ratings for the course during in-person instruction. For the basic mechatronics course, Figure 9 shows that there were not drastic deviations in student evaluations, compared to several years of previous evaluation data when teaching was done in person. (The basic circuits course is in progress for the first full semester being taught remotely.) More importantly, several of these techniques will be useful for improving the courses, making them more versatile and effective after the return to in-person instruction.

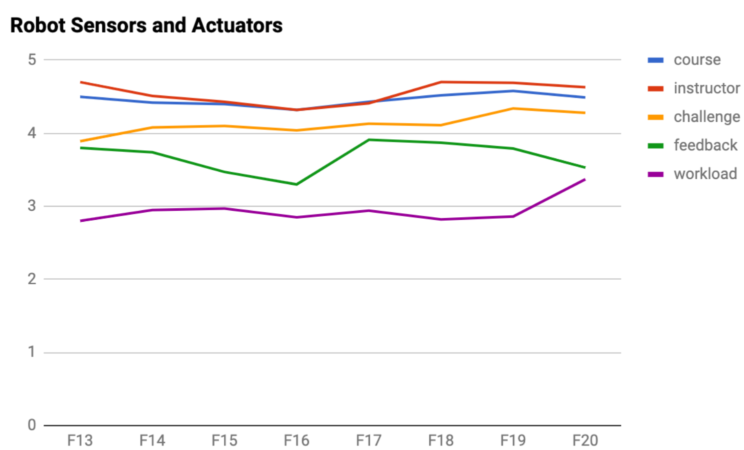

Figure 9. Course evaluations; the Fall 2020 semester involved remote laboratory instruction.

One area where these type of distributed laboratory kits will prove particularly useful even after in-person learning is once again the normal practice is with design projects. The ability to do signal analysis at home, rather than having to hook up circuits only in the laboratory, will be invaluable to students working on challenging projects on their own. Assessment of the effectiveness of these laboratory exercises will continue, comparing in-person only methods with remote-learning methods. Furthermore, future academic years will allow for the assessment of the distributed laboratory kits when integrated with traditional laboratory exercises.

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