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Adapting through a Pandemic: Creating a Hands-On Mechatronics Laboratory with Team-Based Collaboration for Remote Learning

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Adapting through a Pandemic: Creating a Hands-On Mechatronics Laboratory with Project Team-Based Collaboration for Remote Learning

Abstract

This paper introduces a hands-on laboratory curriculum for an undergraduate mechatronics course that delivers a team-based collaborative student experience for remote learning. COVID-19 pandemic created unexpected challenges for educators, where in-person teachings had to quickly transition to remote learning. This significantly impacted learning outcomes for hands-on laboratory courses by students not having access to laboratory equipment and the difficulty to follow the education practice "learn by doing" in the confines of their home. A remote laboratory curriculum is introduced with a series of hands-on mechatronic labs. Three individual student labs introduce how to operate a microcontroller, process infrared sensor signals, and program digital communication displays. Then two team-based collaborative labs explore how students can transmit/receive signals to control a servo using an ESP32 microcontroller with wireless communication over a bi-directional shared server. Then a course project on remote teleoperation is introduced for student-to-student collaboration at home. The learning experience gave students insight into a growing technological area, where teleoperation is in such fields as in-home healthcare, space and ocean exploration, and human-machine collaboration. Student survey results provided positive feedback on their ability to meet project requirements with the challenges of being at home instead of having an in-person learning environment.

Introduction

In-person classroom teachings have been the education norm for K-20 education [1]. Over time, a new form of pedagogy known as distance education or remote learning was created that physically separated educators and students in transferring knowledge. This was mainly due to the advancement of technologies and the internet that created an important sector within the education system [2]. Remote learning has garnered a strong interest for a variety of reasons; by allowing a larger inclusive student population, providing asynchronous teachings for more accessibility, and reducing tuition and institution cost [3]. However, not every institution has a distance education program in place while others may only have an online minor education program or certification [4]. COVID-19 pandemic instantaneously impacted the higher education system where remote learning was no longer an option for both educators and students, but more of a necessity [5]. Most universities were not prepared and had to adapt to remote learning practices while causing severe disparity for students of color, students with disabilities, and students who are caregivers [6]. Thus, pedagogy for remote learning needs evolution to provide a more equitable teaching structure for all participants.

Remote learning can be an advantage for a particular degree plan, while it can also be a hindrance. Hands-on engineering courses can be negatively impacted by not providing the required engineering practice for the students to meet the learning outcomes [7]. This applies to mechatronics that involves firsthand teachings across different engineering fields (i.e., mechanical, electrical, and software engineering) to design and build an electromechanical system to meet desired automation tasks [8]. Typically, a mechatronics course contains weekly lectures paired with in-person laboratory sessions to put mechanical and electrical theoretical concepts to real-world practice [9]. Furthermore, a semester project is generally introduced to provide students a team-based assessment to design and build a smart, mechatronic system to solve a given problem statement. A course that desires hands-on learning can be very challenging to include within a distance education program.

A variety of mechatronics laboratory curriculum have been developed for remote learning. An internet-based remote laboratory was created on teaching applications of an Arduino microcontroller operating across a web server [10]. Similarly, a National Instrument (NI) myRIO controller programmed using LabVIEW was used for an interactive learning experience in operating an electromechanical laboratory equipment across a designated network connection [11]. Another curriculum advancement included a remote operated laboratory having an electronic test breadboard with standard instrumentation equipment (i.e., function generators, oscilloscopes, etc.) using LabVIEW and NI PXI-8176 controller to control the switch matrix of multiple circuit configurations [12]. This allowed remote students to perform circuit analysis and monitoring of an actual built circuit across a server. However, it required an onsite instructor or lab technician to change out physical components and probes for the laboratory to be operational. In all, these approaches include a dedicated remote laboratory equipment located at an institution or center operating across a designated Virtual Private Network or web server for communication [13]. Furthermore, these remote laboratories are between an individual student and the remote equipment that are based on a specific mechatronics topic area instead of broad areas for a semester-long mechatronics laboratory course.

The availability of wireless internet networks (e.g., Wi-Fi) has allowed communication signals connect to nearby devices, which has expanded the growth of Internet of Things (IoT) in consumer products. Mechatronics education can play a pivotal role to teach and train the future engineering workforce in IoT and related fields [14]. Moreover, newly developed low-cost microcontrollers with built-in Wi-Fi and bluetooth capabilities can take full advantage of sending data from one location to another untethered [15]. Developing a remote hands-on laboratory curriculum can give student collaboration with newfound technologies beyond what is encountered within an in-person classroom.

The proposed work gives a complete hands-on mechatronics laboratory curriculum for remote learning with a team-based collaboration project using Wi-Fi for an at home mechatronics education experience. The challenge with remote learning is the difficulty to administer team-based collaboration on physical hardware and working within a student team environment. A Wi-Fi project focused on creating a teleoperation system allows students to think beyond the typical in-class mechatronics project. Teleoperation is a term that implies operating a system from a distance or remotely, which the project theme goes well for remote learning. Such fields as autonomous remote vehicles, robot surgery, and space exploration use teleoperate mechatronic systems. Also, a team-based project incorporates a sense of connection between students [16]. To prepare students, a series of mechatronic labs are administered to learn fundamentals of mechatronic for how to operate a microcontroller, work with infrared sensor signals, and program digital displays for instructional scaffolding leading to two microcontroller Wi-Fi labs. The Wi-Fi labs pair students to connect to a shared server that each can send/receive signals to reading local sensors or controlling a motor. This provides a foundational knowledge for student teams to meet the project objectives in developing a remote teleoperation system.

Mechatronic Fundamental Lab Curriculum

The mechatronics lab curriculum is a 16-week course taken by mechanical and electrical engineering students typically in their Junior or Senior year of their engineering degree plan.

Mechatronics has a variety of topics that can be found within a curriculum, but this curriculum was tailored using a backward design approach to meet the course project objectives [17]. The project objective was to pair students in creating a remote teleoperation system using Wi-Fi. A lab series of mechatronic fundamentals are administered to build the necessary student skills leading up to the semester project. It includes three labs that teach fundamental mechatronic concepts of microcontrollers, communication displays, and infrared sensors. Then two Wi-Fi labs are given to educate students about connecting a microcontroller to a shared internet server thru Wi-Fi, and how signals can be sent/received between peers [18]. Table 1 summarizes the proposed laboratory curriculum with the following sections describing the design curriculum.

Table 1: Overview of Mechatronic Laboratory Curriculum

Lab Number	**Lab Topic**
Fundamentals of Mechatronics	
1	Arduino Microcontroller Quick Start
2	Communication: LCD & Digital Displays
3	Infrared Sensing
Wi-Fi Labs	
4	Wi-Fi Setup with Microcontrollers
5	Wi-Fi Teleoperation for Servo Control

Lab 1 - Arduino Microcontroller Quick Start

Lab 1 provides a general overview of what is a microcontroller and their common peripherals used in mechatronics. Majority of students had no prior knowledge of microcontrollers, so an Arduino Mega 2560 with an Atmel ATmega2560 processor was chosen [19]. An Arduino microcontroller is a popular, open-source device for novice users to rapidly integrate into a mechatronics system [20]. Students were required to purchase an Arduino Mega and other lab-related components to their remote location by the second week of the semester. The lab learning outcomes were to understand the Arduino Mega breakout board and its peripherals that include 16 10-bit resolution analog inputs, 54 digital I/O pins, and specialized functional pins such as RS232 TX/RX serial communication, 8-bit pulse-width modulation (PWM) output, and external interrupts. Students were to download and set up Arduino's integrated development environment (IDE) with C/C++ libraries on a student's personal machine. The Arduino IDE is the software interface where all programming is done and compiled to the microcontroller. Once the software environment is configured, then students are to wire a light-emitting diode (LED) resistor circuit to a breadboard to control the LED illumination using their microcontroller. For the labs, students are provided pseudocode as an informal program flow in programming the syntax to interact with their electronics.

Lab 2 - Communication: LCD & Digital Display

The next lab is to learn how to send strings from the microcontroller to a liquid crystal display (LCD) as a requirement for the teleoperation project. A project requirement (see section Project - Remote Teleoperation) states that students can send instruction across a server while receiving a message through an LCD as verbal communication is not allowed during the teleoperation sequence of the project. The open-source Arduino LiquidCrystal library provides functions to send strings to a commonly used monochrome LCD1602 display screen, where students programmed specific strings and have the message display through the LCD. Another form of communication students learned was to operate a single digit, 7-segment 74HC595 display. The 7-segment display emulates 7 LED resistor circuits as in Lab 1, which can each be controlled by sending a byte of binary numbers to display a number from 0-9. This teaches students to create a counter digital display to meet another project requirement.

Lab 3 - Infrared Sensing

The last individual student lab is learning how to detect infrared (IR) emitter and receiver sensing. Students at home were to build an IR emitter (part number: LTE-4206E) and receiver (part number: LTR-3208E) to sense IR detection. A LED was used as a visual indicator when sensing was received between the IR emitter and receiver (Figure 1). An interrupt was assigned to the Arduino to detect when the IR is sensed for decision making purposes.

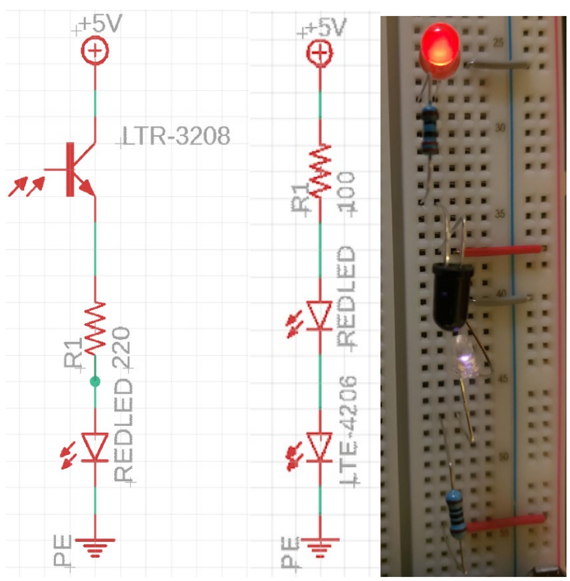

Figure 1: Actual IR emitter and receiver circuit with LED sensing indicator

Mechatronics Wi-Fi Lab Curriculum

The Wi-Fi labs involve the Arduino Mega paired with a low-cost ESP32 microcontroller with Wi-Fi capabilities to send/receive messages through MQTT (Message Queueing Telemetry Transport) server. The MQTT server acts like a messaging hub, where devices can send data to a specific channel that other devices can subscribe to receive the data [21]. MQTT server has its benefits that it can be free to access, no software installation is required, and can be used with the

Arduino IDE. Both the ESP32 and the Arduino Mega can be programmed through the Arduino IDE with an open-source MQTT library.

The ESP32 and Arduino Mega can complement each other. The ESP32 only has 34 general-purpose I/O pins, which include 15 analog pins. Pairing the ESP32 with an Arduino Mega can substantially increase the number of analog/digital I/O pins to develop large scope projects with multiple sensors and motors. The ESP32 can behave as a medium to send/receive data through the MQTT server from the Arduino Mega. The UART serial communication protocol between the ESP32 and the Arduino Mega allowed both microcontrollers to share TX (transmit) and RX (receive) signals between them. For example, the Arduino Mega to receive data will have the RX pin connected to the ESP32 TX pin. This is reciprocated for the ESP32 to receive data, then its RX pin will be connected to the Arduino TX pin. Note that the ESP32 serial pins run on 3.3V and the Arduino Mega runs on 5V, so a voltage divider can step down the Arduino TX/RX voltage lines to allow the ESP32 accept the signals.

As the ESP32 has integrated Wi-Fi, it can transmit data to the server by publishing or receive data by subscribing. The Arduino Mega sends low-level command signals to the ESP32 that then flows to the MQTT server. This whole process forms a communication pathway between the Arduino Mega, ESP32, and the MQTT server. If a message is received from the server, then the path starts at the server to the ESP32 and ends at the Arduino Mega. This forms the communication architecture between two students with sets of Arduino Mega and ESP32 microcontrollers connected to the same server as shown schematically in Figure 2.

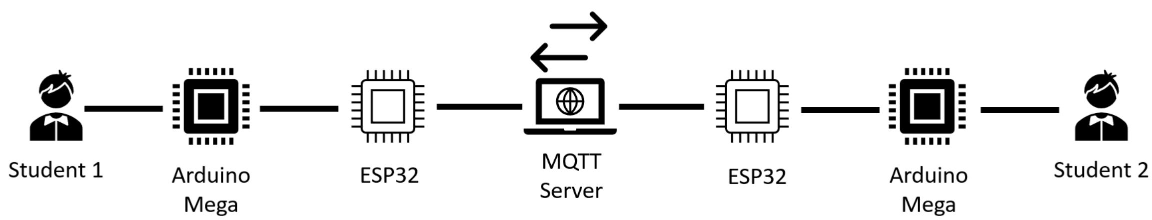

Figure 2: Arduino Mega, ESP32, and MQTT server communication overview between Students

Lab 4 - Wi-Fi Setup with Microcontrollers

Lab 4 introduces students to the Arduino Mega, ESP32, and MQTT server communication setup. The lab objective is to integrate the microcontrollers with the MQTT server as shown in Figure 2 to have successful communication between a pair of students at remote locations. Installing the PubSubClient Arduino library has a set of functions to connect through a MQTT server using an ESP32 [22]. The microcontrollers can then communicate through Wi-Fi to a publish and subscribe network. There are many options for which MQTT server to use with the PubSubClient library. The EMQ X was the suggested MQTT server, as it is no-cost for users and has a simple user-friendly interface [23].

The MQTT server has a few settings that must be set up before creating the server: naming the server, generate a client ID, use the default host as EMQ X, use port 8083, and set path starting with /mqtt. See Figure 3 for the declared settings.

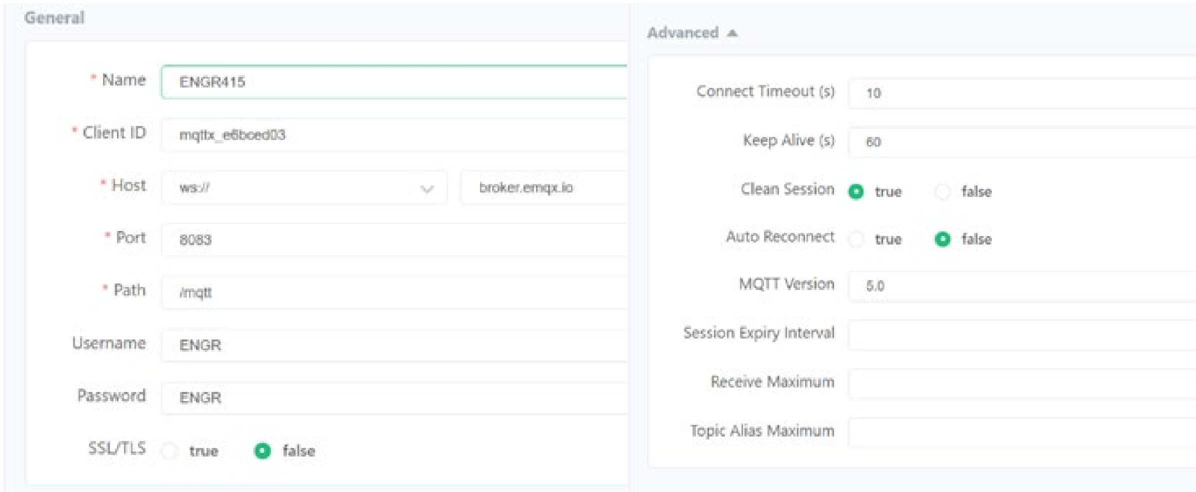

Figure 3: EMQ X MQTT server settings

After the server is created, a new subscription channel must be established. This is the channel where all the data will be sent to and read from. This step involves selecting the new subscription option and naming the subscription channel. At the bottom screen of the new subscription channel, change the payload to plaintext and add the name of your subscription to the topic line to complete the setup.

After preparing the server and running the PubSubClient code provided within the library download that includes the server and internet connection input details, the ESP32 serial monitor will display a message showing the connection is complete (see Figure 4). The paired students can perform a test to enter a message in the server that should see the message on the Serial Monitor. Confirming back and forth communication between remote students, the next lab can be attempted.

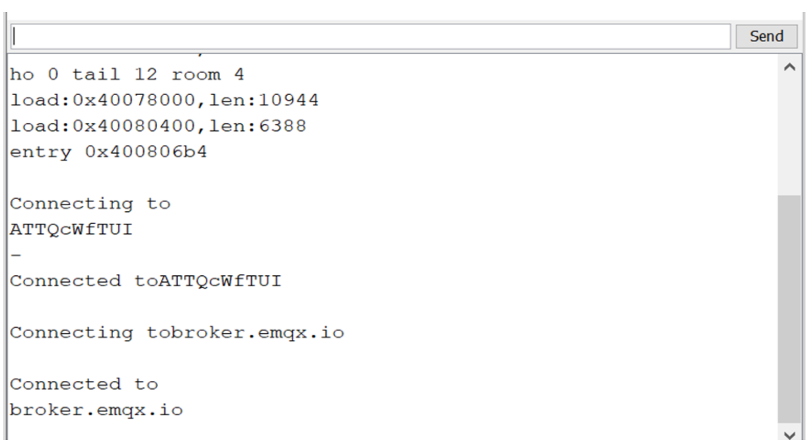

Figure 4: ESP32 serial monitor connection message to MQTT server

Lab 5 - Wi-Fi Teleoperation for Servo Control

The last lab involves teleoperation between two collaborative remote students with an analog joystick and a servo motor controlled by PWM 50 Hz signal and duty cycle change [24]. The lab objective is to control a servo motor rotation with an analog joystick through teleoperation. Setting up Wi-Fi through the MQTT server from the previous lab, students can then send a joystick user input as a master operator to the MQTT server and have the standby operator receive the signals that will control a servo motor at a remote location. Each student developed the same hardware setup at their home to allow each to experience both master and standby operator roles. For reduced latency and faster response time, the joystick should be connected to the ESP32. The Arduino Mega is to perform the low-level servo motor control. As the MQTT server only outputs string data types, programmable code is relied on to develop strings and data type conversions adequately between the ESP32 and the Arduino Mega. The following figure shows the lab process flow between a student teleoperating a servo motor at a remote location through a shared server using Wi-Fi.

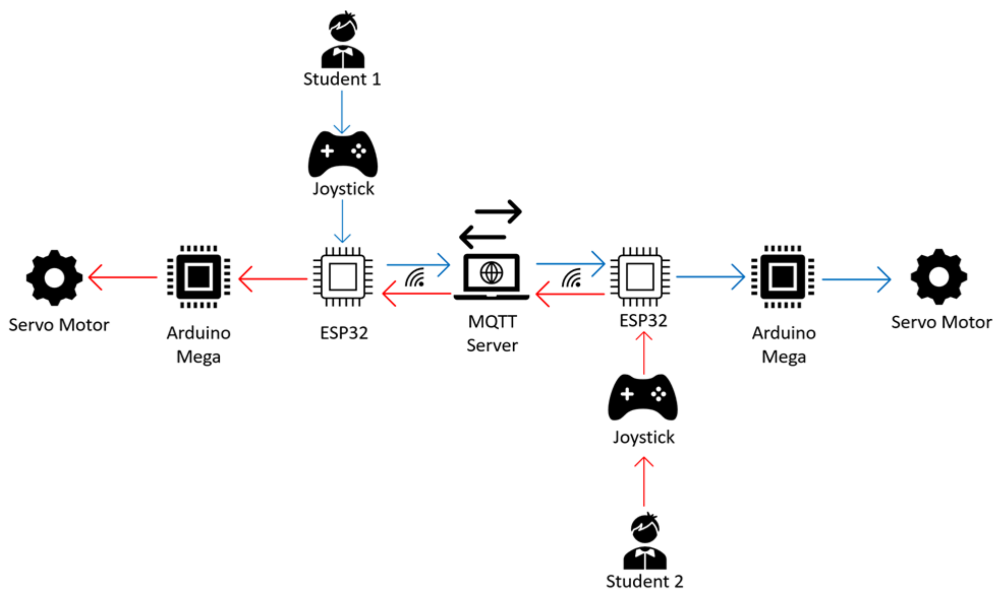

Figure 5: Lab 6 servo control teleoperation using Wi-Fi at remote locations. Student 1 (blue line) and 2 (red line) has a communication workflow going back and forth through the MQTT server medium between a student with joystick input signals to controlling a servo motor.

Project - Remote Teleoperation of a Mechatronics System

A mechatronics project allows students to apply design skills, project management, and hands-on manufacturing to solve a thought-provoking multidisciplinary engineering problem [25]. Going through a worldwide pandemic with COVID-19 has impacted everyone in their daily lives. Technology has always overcome societal challenges and engineers/scientists are typically at the forefront to take on those challenges. This inspired the project problem statement to have students stay connected remotely while expanding their technology awareness with extended distance technologies, such as the area of teleoperation. Teleoperation is controlling a system or device remotely by a human operator. The project purpose is to have a remote learning experience for teams of two students in creating their own remote teleoperation mechatronic system at home that encompasses actuators, sensors, and software programming using a microcontroller with Wi-Fi capability. The project description entailed a space exploration theme using remote teleoperation to engage students in a particular field. The project engagement aspect was to imagine a master operator located at a mission control station on Earth that needs to communicate with a standby operator located on the International Space Station (ISS) to perform decisions or actions based on the master operator commands. This project is to emulate back and forth communication of a remote manipulator scanning on the ISS workspace area while providing guidance of local detection and decision making. Master and standby operators may not communicate with each other through visual camera or audio microphone/speaker. The only form of communication between operators is analog to digital signal conversion through Wi-Fi connected to a shared MQTT server. This form of student engagement, particular in the space industry such as NASA, has proven success with integrating industry-related problems into mechatronics education [26].

The project objective is to have a master operator (student 1) joystick control a remote planar manipulator located at a standby operator's (student 2) location through Wi-Fi using a shared server. The standby operator can send messages to the server that the messages are received and printed to a local LCD1602 display screen at the master operator's location. The master operator has no visual of the manipulator in motion. Therefore, the standby operator can provide instructions to the shared server of the up/down/left/right direction for how to control the manipulator in scanning the x-y (minimum 12 inch x 12 inch) planar surface. The planar manipulator contains an IR receiver at its end-effector, where the IR receiver points downward to the planar surface with six equally spaced (2 x 3 grid) IR emitter locations to create a touchless IR sensing detection between an IR emitter and receiver. Figure 6 displays a rendered CAD design and the manufactured x-y planar manipulator with the IR emitter surface for scanning.

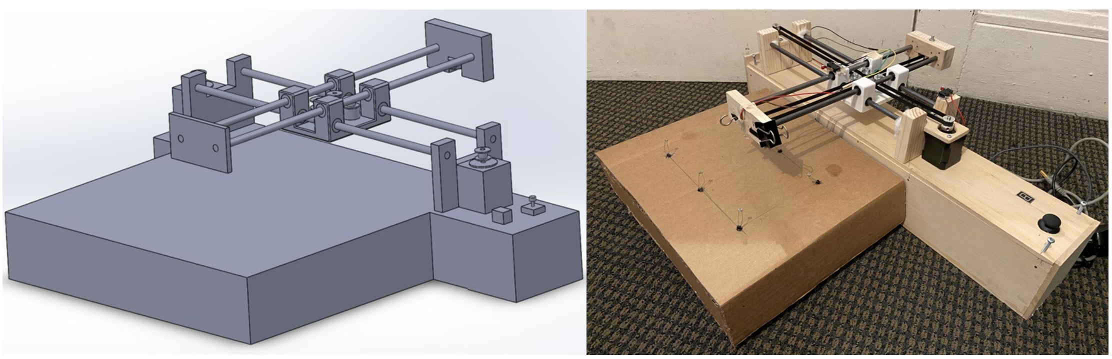

Figure 6: Standby operator x-y planar manipulator with IR sensing ports 2 x 3 grid for remote control scanning and detection. Left image demonstrates a CAD rendering and the right image is the built system.

When the planar manipulator is roaming and makes IR sensing detection, then command instructions are automatically sent to the master operator's LCD display through the shared server. The commands will notify the master operator to physically activate the designated sensor on a sensory operation board built by the master operator at their remote location. The sensory operation board contains six different sensors (e.g., visual, pressure, audio, motion, force, etc.) to activate, where each sensor is designated to its assigned IR emitter port on the manipulator's scanning surface (see Figure 6). The type of sensors (e.g., ultrasonic, proximity, tilt, force sensitive resistor, etc.) is chosen by the student team, but majority are sensed through analog with their respective signal conditioning circuit. Figure 7 demonstrates the CAD and manufactured sensory operational panel that a master operator built at home.

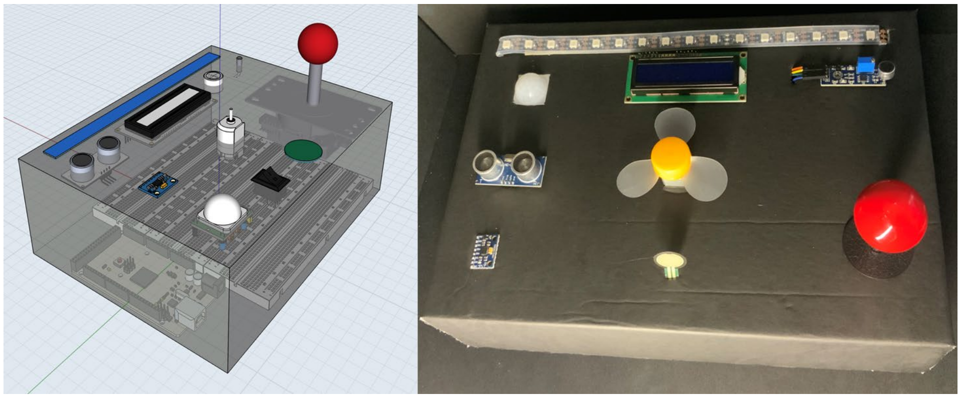

Figure 7: Master operator joystick controller and sensory operational panel. CAD rendering to the left and actual built panel shown to the right.

Once the master operator activates the designated sensor, then a signal is sent back to the shared server to notify the standby operator that sensor activation is complete where a single digit display sensory counter is incremented by one. The project mission is for each team's teleoperation system to detect all six IR sensors through the remote manipulator scanning and sensor activation by the master operator.

Student teams were given ten weeks to propose design concepts, manufacturing, and final project validation. The project timeline began after the lab 5 Wi-Fi with teleoperation, so students had the appropriate background and understanding for how to apply Wi-Fi communication to a mechatronics system. Table 2 describes each project milestone.

Table 2: Remote Teleoperation Project Milestones

Milestone	**Deliverables**
Project Proposal (Duration 1 week)	Student teams develop a 2-3 page project proposal explaining how their proposed teleoperation mechatronic system will meet the project requirements. Support documentation includes engineering design sketches, control system block diagram, decision making flowchart, and manufacturing methods.
Design Process (Duration: 3 weeks)	Create all final design documentations before the manufacturing phase. This includes design development of mechanical CAD, electrical schematics, and software pseudocode. This milestone provides a blueprint for student teams towards manufacturing. A final build of material is an important deliverable, so materials can be ordered to their remote location.
Manufacturing (Duration: 3 weeks)	The manufacturing phase includes building mechanical and electrical subsystems with their own respective checkpoints. Each week team check-ins are required with the instructor through video conference to keep teams on pace and discuss any engineering issues prior to final demonstration.

Functional Demonstration (Duration: 2 weeks)	Two types of demonstration milestones were required. First week is to have a subfunction demonstration of each student's standalone mechatronic subsystem. The subsystems include working sensors on the sensory operation panel and the planar manipulator is actuating in a x-y direction. Second week is for full function demonstration that teleoperation is achieved between remote students across a server that displays project objectives were met.
Final Presentation (Duration: 1 weeks)	Team presentations give an overview of the design and manufacturing process of their project, explain challenges working on their project remotely, and how they overcame those challenges. A short video demonstration of how their teleoperation system works was required.

The first team milestone is to review the project requirements and brainstorm high-level design concepts to create a project proposal. The proposal is reviewed by the instructor before proceeding to justify it has intellectual merit. Then the design process included mechanical, electrical, and software engineering methods to design a mechatronic system using the necessary engineering software tools. Mechanical design was to develop a final 3D CAD model (e.g., SolidWorks) and determine the materials needed for manufacturing. Final dimensions and parts selection will provide the build of material to make a project purchase order. Electrical design is to generate the circuit schematics (e.g., EAGLE) and necessary circuit analysis (e.g., LTspice) to determine the main circuitry needed for the appropriate sensors, signal conditioning, and servo motor drivers that will be interconnected to the microcontrollers for each local system control. Software design involved creating a state machine diagram with a state transition table for how the teleoperation system should operate. After completion of a design review between the instructor and team, the manufacturing phase for system building is performed for the next three weeks. Finally, the weeks of demonstration leading up to final presentations include subfunction demonstration by both master and standby operator of their standalone state. Then a full functional demonstration of teleoperation between two students remotely operating their mechatronic systems is requested prior to final team presentation.

Student Evaluation

The project required much effort from the students by not having in-person guidance from the instructor nor access to on campus engineering test equipment. However, having a pair of students collaborating on a project remotely can bring a supportive environment that students typically would receive in-person. A survey was administered to 17 students to obtain student feedback on the project scope and understand the resources they had available at their remote location. Table 3 provides survey results captured after the project description was introduced.

Table 3: Student Survey Questionnaire

Manufacturing Equipment	
Question 1: What general manufacturing equipment do you have in your possession at home?	**Percentage**
Power Drill	44.44 %
Bandsaw	16.67 %
3D Printer	11.11 %
Other equipment	27.78 %
Electronic Test Equipment	
Question 2: What general electronic engineering equipment do you have in your possession at home?	**Percentage**
Digital Multimeter	37.5 %
Variable Power Supply	25.0 %
Oscilloscope	12.5 %
Function Generator	6.25 %
Other equipment	18.75 %
Student Confidence Level	
Question 3: What level of concerns do you have in completing the project objectives during remote learning?	**Percentage**
Very High Concern	17.65 %
High Concern	17.65 %
Slight Concern	41.18 %
No Concern	23.53 %

In terms of equipment accessibility, the results revealed most students had at least one form of engineering manufacturing or test equipment. Rapid prototyping is a key element within a semester-long mechatronics course [27]. High school or early-career college students are getting trained on basic rapid prototyping equipment or tools (i.e., 3D Printer, Drill, etc.) that have become more common usage for at home use. The most accessible equipment were power drills and 3D printers being 72% of the control group. Other equipment consisted of woodworking tools, soldering stations, and 16% had access to different power tools. Similarly, electronic test equipment was surveyed that over half had access to a digital multimeter or power supply, whereas about 19% had an oscilloscope or function generator at home.

Acquiring student feedback for students' confidence in meeting the project requirements was important to make sure students' success was considered for the proposed project. About 24% had confidence the project can in fact be accomplished in a remote setting, while the remaining had different levels of confidence from slight to very high concern the project can be achieved. However, a survey question was asked if students would rather change the project scope and focus on a simulation-based (non-hardware) project during remote learning. Overwhelmingly, 82% stated no and wanted to continue with the proposed project rather than have a non-hardware project. Then a question was polled if students preferred individual work instead of a collaborative project working with a teammate. Majority of students at 94% preferred to take the collaborative approach with a team-based project while students are working remotely.

Conclusion

The proposed curriculum considers the challenge of developing a hands-on curriculum within the confines of remote learning. A series of hands-on individual labs were introduced to provide students with the fundamentals of mechatronics, tailored to accomplish the project objectives. The labs consisted of understanding the Arduino microcontroller, reading analog sensors, and communicating through digital displays. Then two team-based Wi-Fi labs were administered to bridge students between the fundamental labs and the start of the team project. The labs expanded students' knowledge of using wireless communication within an introductory mechatronics curriculum. It involved taking a low-cost microcontroller with Wi-Fi capability to connect to a shared MQTT server to send/receive signals between students in a remote setting. This provided a gateway to introduce the field of teleoperation, which was the basis of the proposed project. Teams of two were tasked to develop a teleoperation system between a master and standby operator of controlling a planar manipulator to scan a sensory surface for detection and decision making. All the hardware and software were created at home with each student having various resources at hand. Overall, the project instilled a strong, team-based collaborative effort between students during a difficult time, such as the COVID-19 pandemic. In conclusion, this work can expand the capabilities of a mechatronic curriculum when considering it within a distance education program.

Acknowledgement

To all the hardworking students who participated in this new form of mechatronics curriculum during challenging times within a pandemic and achieving success in their projects.

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