A Reproducible Solution for Implementing Online Laboratory Systems through Inexpensive & Open-source Technology

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Abstract

Laboratory experiences are a crucial part of the undergraduate engineering curriculum. With coursework, college programs, and professional interactions increasingly being performed online the natural evolution of a 'digital-first' culture suggests that traditionally hands-on educational activities should find themselves represented online as well. Transitioning laboratory-based exercises online is difficult, time consuming, and sometimes costly. In addition, the efficacy of an online laboratory experience as a worthwhile educational tool has not been explored with depth. This study focuses on the details and benefits of incorporating laboratory experiences with online infrastructure with the perspective of optimizing development time and cost. The purpose is to use FOSS (free and open source software) in addition to other open source solutions to develop modular, scalable, and easily deployable remote laboratory infrastructure capable of interacting with traditional equipment over network connections.

Introduction

It is commonly accepted that one of the best ways to learn technical skills is through hands-on experiences. Be it through apprenticeships, internships, laboratories, or bootcamps, an interactive experience provides concrete, engaging, and fulfilling learning opportunities. By spending time personally carrying out a task, the brain forms neural connections which make it easier to remember and duplicate the task. The understanding of cognition and epistemology has grown throughout the entirety of the history of the human race. Masters pass down skills by having pupils perform those skills according to their instruction. However, with the rise of the digital age, the question becomes, can the dissemination of all concrete knowledge be conducted via computers just as well as through physical interactions. And if so, then how?

The Impact of Remote Laboratory Systems on Education

The digital world has become an integral part of the lives of faculty and their students and is now irrevocably intertwined with daily routines. As such, society grows ever more comfortable interacting with the world through a digital medium and seeks to find new avenues to do so and new virtual environments to explore. Therefore, it naturally follows that transitioning the whole of education towards a system which is more frequently used by digital natives may be in the best interest of future generations. The purpose of this study is to create a case for implementing remote, on-line laboratory experiences that can successfully fill the same intellectual need as their physical counterparts. The benefit of achieving this goal is similar to that of all on-line instruction, to reach more students and to make education accessible. The chief drawback is that creating the network infrastructure necessary to implement on-line experiences as a substitute for physical laboratory work is difficult and costly. This study also seeks to find and build open-source solutions to this problem using inexpensive hardware, open-source software, and simple network configurations that may add to the list of best practices built by previous and current researchers.

Impact on Students

Remote laboratory systems offer unique benefits to how students retain information. By providing students with a more open platform to access knowledge, rather than traditional physical interactions, it is possible to see positive effects on engagement and learning. Nabil Lehlou et al. (2009) conducted a study in which students in two different fields (Industrial Statistics and Manufacturing Systems) performed lab exercises and recorded how the students felt they understood the material before and after the lab. The results provided a clear indicator that the students felt the remote lab system provided a beneficial educational experience as six out of eight in Industrial Statistics and eight out of eight students in Manufacturing Systems reported an increase in confidence in the subject material. In addition, five out of eight students in Industrial Statistics and eight out of eight students in Manufacturing Systems reported a drastic improvement in their confidence for their respective fields.

A separate study performed by H. Vargas et al. (2010) found similar positive results. They provided 120 students across seven universities with remote laboratory experiences. The research indicated that the full lab experience included performing an actual lab over the internet, which required students to reserve a time to use the lab resources. The response by the students indicated that they enjoyed the system as well as found it useful in understanding the respective course content. According to the results, 69% of the students felt satisfied with the system and 19% felt strongly satisfied. Additionally, 51% of students felt that the remote lab was better than traditional methods, 25% felt it was equal to traditional methods, and 15% felt it was much better than traditional methods. These results strongly assert that remote laboratory experiences not only have a place in the future of education but can have a large impact on its quality.

Key Features Needed

To better understand what makes remote lab systems effective and their impact on students potent, it is critical to understand what key features are common among these systems. In a study performed by P. Bisták et al. (2011) at the Slovak University of Technology in Bratislava, Slovakia, it was outlined that a remote lab system server could provide the client (user) with text messages, numerical data, graphs, animations, and video clips. The system could interface with sensors and cameras in order to collect useful information and statistics for the client. The setup involved a front-end GUI being served to a client, which in turn communicated over TCP/IP to a remote server. Information could be transmitted in either direction between the server and the client with data and commands running back and forth. The server would have access to the local hardware of the lab system and be able to send any commands received from the client to the hardware. Additionally, it would be able to collect output data from the lab hardware and send it back to the client.

Another remote lab study was performed by T.J. Mateo Sanguino et al. (2012) at the University of Huelva in Palos de la Frontera, Spain. In this study a similar setup was implemented with a client providing user access to a remote server, which was in turn connected to a lab system. The user would have the ability to control computer devices on a rack through this setup and perform multiple remote labs. An interesting point to make which differentiates this study from the above is that it does not send photos back to the user. The labs performed did not require cameras or video, instead relying on numerical data to provide the pertinent observation. This is an important point to make as it shows that every lab system is different and there might not be a "generic" or "one-size-fits-all" approach. If this is the case, then a truly reproducible lab system must provide means by which different hardware or software peripherals may be added or removed depending on the needed application. However, at a minimum it appears that a remote laboratory needs a client-server system and some basic means by which to send text or commands between the client and server.

Making Labs More Personal

As humans are social and emotional creatures, it could be argued that experiences which leverage those traits would aid in the retention of information. It could also help explain why recent concepts such as social media have become fast staples in cultures around the world. They simply exploit the natural desires of people. Similarly, despite being called "remote", it might be possible to use remote lab systems to improve learning through social, emotional and personal growth. A study performed by C. Terkowsky et al. (2013) at TU Dortmund University in Dortmund, Germany focused on the personalization of the remote laboratory experience.

They referenced a theory on education and learning called “Kolb’s Experiential Learning Cycle” wherein multiple stages of learning are introduced. These stages are Concrete Experience, Reflective Observation, Abstract Conceptualization and Active Experimentation. According to the theory, they create the “learning experience”. Armed with this information, the study introduces the concept of an E-Portfolio. This E-Portfolio provides users of remote labs with the ability to record the work they performed and document their findings. The concept of this portfolio does not stop at being a simple digital notebook, however. The study asserts that this portfolio can be used by professors to check on students’ work or be opened to the public in order to add a social dynamic. The study calls the social aspect a “community” and says that it can facilitate learning. To reinforce the main point, by adding a social aspect, be it with classmates or with the world, users will have a greater feeling of connection with their work and might retain more information.

Another study performed by Z. Nedic (2013) at the University of South Australia shines light on the collaborative aspect of remote labs. The study saw international students organize themselves autonomously to complete group lab assignments and recorded their planning and communication. The results showed that students, despite being from different countries, exhibited politeness when trying to create social groups and complete the remote labs. The study gives hope to the notion of creating a more connected educational system where students from around the world participate in the same curriculum. This in turn also facilitates international cooperation and communication in the real world, as a large amount of professional communication is done remotely.

One study performed by Qing Ding et al. (2017) as joint research between China and the USA focused on a remote learning system which tried to supplement a lack of in-person lecture time with online tutors. Teams of students would have higher-level students assigned to them to oversee their progress and help them when necessary. According to the study, these “tutors” were from numerous locations throughout China and as a result would not have been able to help the students without this remote system. By adding remote tutors to the learning system, most students responded by saying that their performance in school improved “greatly” or “largely”. With this information in mind, it might be important to consider having remote human aid even in virtual lab systems, as difficult concepts can sometimes be better explained by another person.

Future possibilities

The potential of remote lab systems is growing with the accessibility of the technology. As more researchers and organizations explore the medium, the possible use cases grow. For example, researchers Ananda Maiti et al. (2012) were able to create remote labs which wirelessly controlled robots. This points to a future where online labs can control components wirelessly. This can greatly improve feasibility where wires are not practical, such as with sealed or otherwise non-accessible systems.

Another study performed by T.R. Pearson (2014) created a low-cost FOSS remote lab setup for computer hardware engineering (FPGAs). FPGAs are programmable boards which can be made to emulate numerous computer architectures and circuits. This provides a look into the future of remote labs where entire processors, graphics cards, or other computer architectures can be remotely programmed and uploaded to a device, executed, and then tested.

Research by Muhammad Asraf H. et al. (2018) shows that remote labs with IoT (Internet of Things) devices running in tandem with LabVIEW software is possible. The lab interfaces with a plant console which allows for remote interaction directly with the data. The research illuminates potential labs that allow nuclear and chemical engineering students to gain experience interpreting statistics from nuclear reactors or chemical plants.

In a study performed by Wen-Jye Shyr et al. (2017), a mechatronics lab was created with a webcam as well a graphical representation of the robotic components. This research can easily lead to possible futures where remote labs have enough sensors to be able to recreate the environment in a 3D rendered stream. This may be useful in the case where visibility is low or impractical due to bandwidth limitations.

A Simple Wet Laboratory Setup

A simple water-filled laboratory setup was designed and built to serve as a testbed. The rig is first tested for manual, in-person control, and then augmented with the remotely-accessible infrastructure to create an on-line lab. Figure 1 shows a simple 3D rendering of a laboratory setup that could support an undergraduate course in fluid mechanics, thermodynamics, or heat transfer. The working fluid in the system is water and students observe the fluid's behavior by controlling and measuring various physical properties. The rightmost water bin contains a heating element. The leftmost bin does not and is of a different volume than the first. A pump circulates the water through the system while transducers measure flow rate and pressure. Thermocouples record the temperature in various locations throughout the system. Several inexpensive Sony Playstation 3 Eye cameras are affixed to the aluminum frame of the rig. All components are controlled and monitored through an online interface that interacts with a local host Raspberry Pi computer.

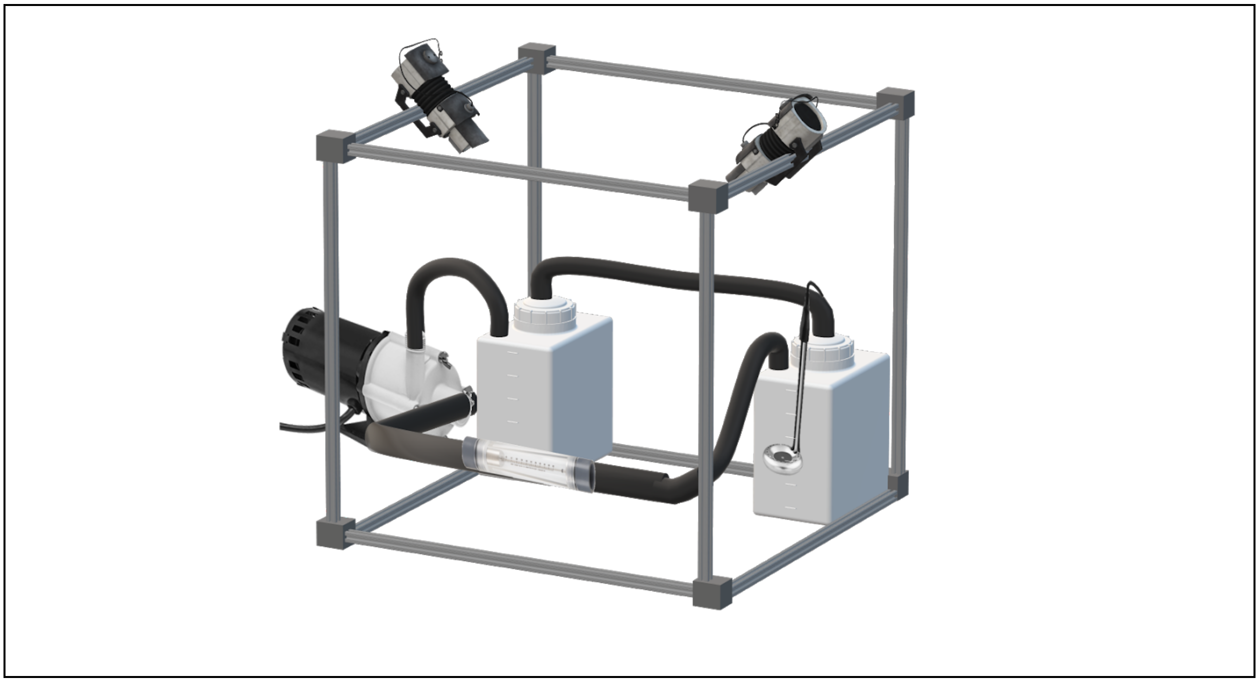

Figure 1: A 3D render of the remote wet lab

Network Architecture

Ultimately, the intent of the project is to build a reproducible infrastructure of network hardware, interface code, and laboratory equipment to provide the next generation of students meaningful access to laboratory experiences. A fully online interface to view, study, and interact with general laboratory equipment is a lofty goal but one that can be achieved at relatively simple levels nonetheless. To make the design most accessible, hardware components must be inexpensive and common, computer or peripheral needs must not be prohibitive, and the software to run it all must be freely available.

Here a simple laboratory hardware-to-network interface is built using the Raspberry Pi 3 (RPi) as the data input and output controller that interacts directly with laboratory equipment, data acquisition devices, computer peripherals, webcams, and any other component which needs to be controlled or used remotely. Figure 2 shows a simple representation of how the RPi is able to transmit user instructions and data between the laboratory and a student accessing the system from afar. In the diagram, remote users send and receive information as http authentication and http proxy communications. Remote users connect to a proxy server that in turn sends requests for information directly to the local laboratory network. Such a configuration is necessary to allow for remote access and addressing to individual laboratory ports or devices.

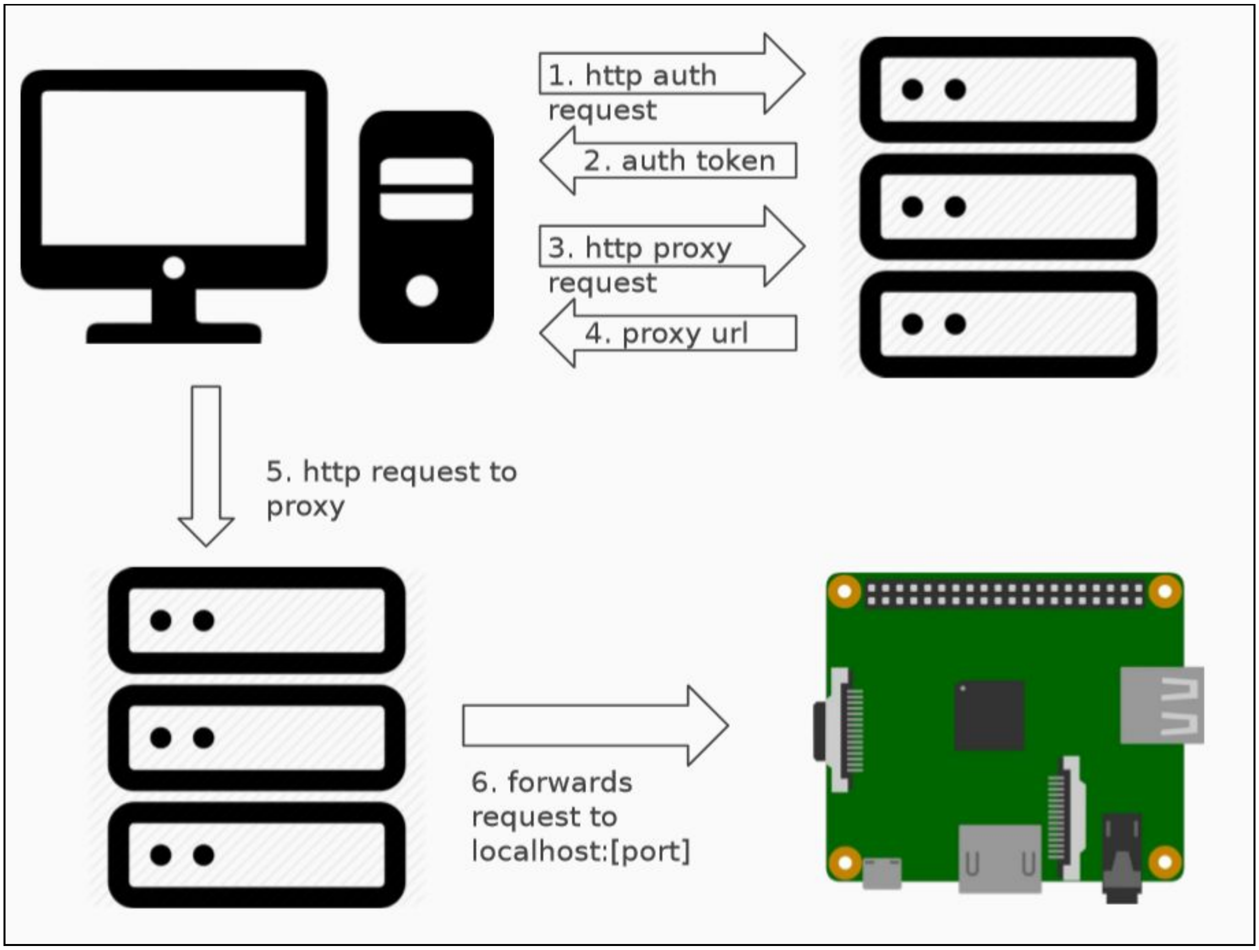

Figure 2: A simplified networking flow diagram

Figure 3 shows a more detailed view of the network infrastructure. Remote users access their local networks from any device such as a tablet, mobile device, or laptop. They are connected via the internet to our proxy server from a front-end application, web app, or mobile app where students are authenticated and registered to access the local laboratory network. Ideally such an application should interface directly with the educational institution's learning management system (LMS) which eliminates the need for the students to maintain additional login credentials on an additional system. Canvas is a common LMS and is used here for student authentication.

The proxy server then connects with the local laboratory network as allowed and directed by the institution's network administrators. This is facilitated by the fact that all laboratory equipment exists on a single network with communications flowing through a router administered by laboratory staff. The Raspberry Pi used here is the local host for all communications from the network though any host machine will do. The RPi was chosen for its cost effectiveness and ability to run only the tasks specific to network communication separate from any laboratory workstations.

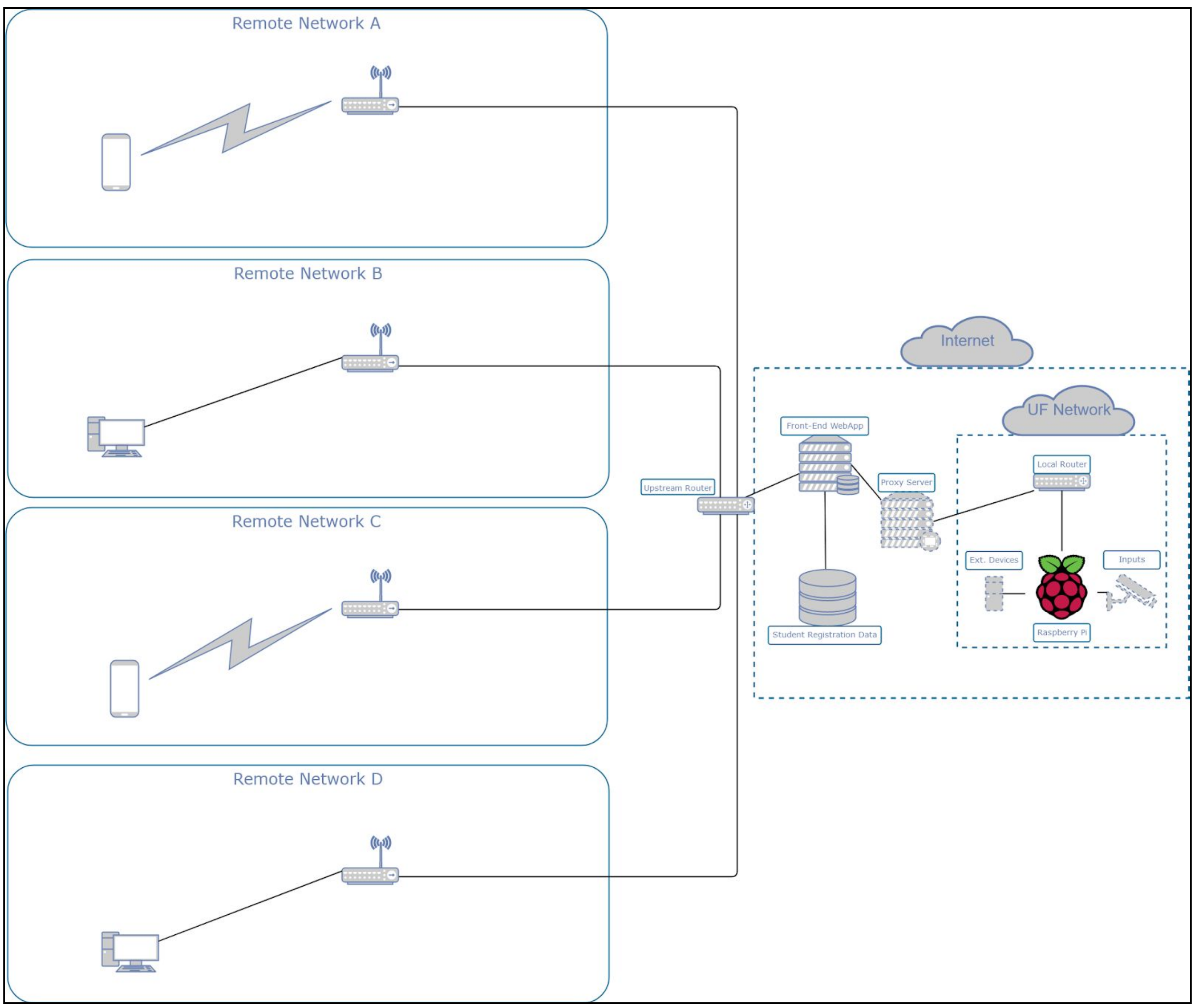

Figure 3: General hardware architecture and data flow

The RPi then manages all connections with the necessary laboratory equipment. Multiple webcams are used to provide visual access to the laboratory from several viewpoints. Video capture devices are used to record any necessary laboratory workstation screens. Any laboratory hardware that needs to be directly controlled or from which to acquire data can be accessed directly by the RPi through any of a number of communication streams, such as a serial connection.

The web application itself is designed to be scalable so that as the number of laboratory peripherals increases, additional communication hardware can be added to compensate. For example, depending on how much video data is requested the capabilities of the RPi may be exceeded. Communication can then continue by adding additional RPi's or other host machines to the system. Figure 4 shows a blank skeleton web app that was developed to accommodate a variety of laboratory interfaces. The app was built with HTML, CSS, and JavaScript and was meant to be easily extended depending on the needs of a particular lab setup. The version of the web app in Figure 4 accommodates video streams from three webcams and a series of general buttons and output fields that can be customized in the code as necessary.

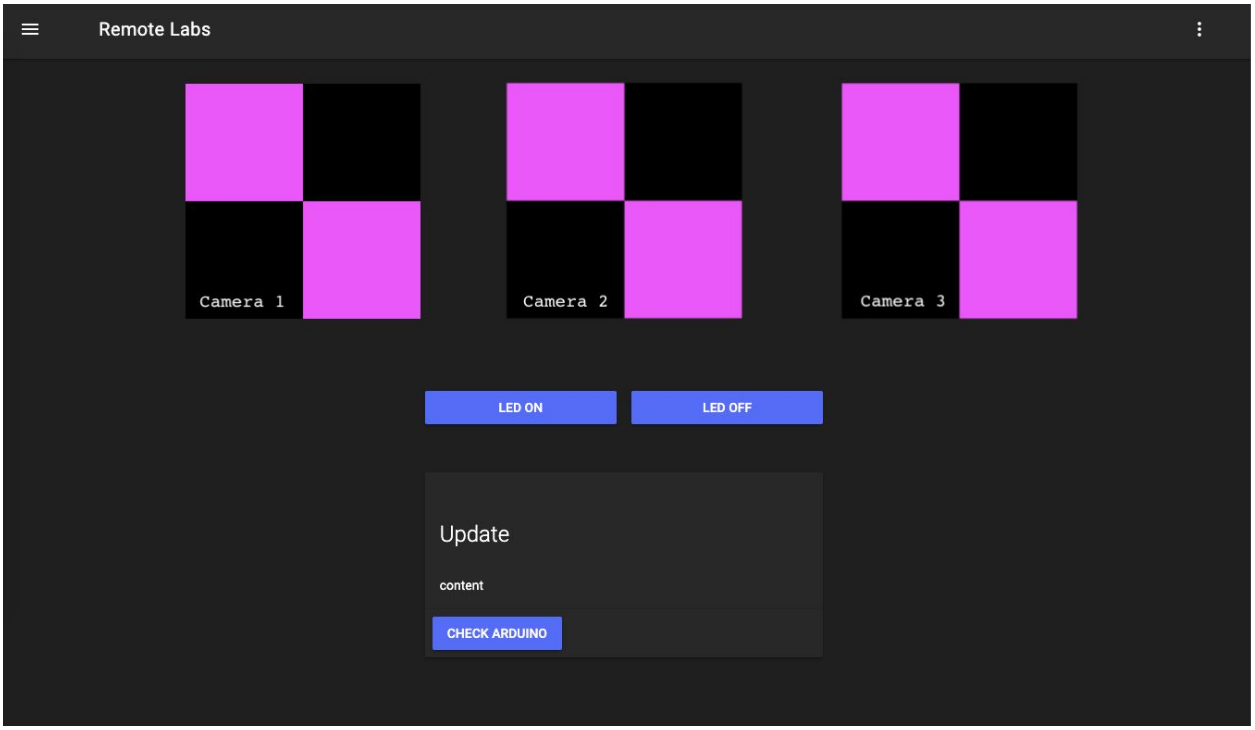

Figure 4: Current Control UI for Lab

Figure 5 shows the basic communication stream between the webapp and the RPi and the major features of the source code that was written to manage it. The user interacts with a custom web app which sends requests to the proxy server through netcode written in JavaScript. The proxy server then communicates with the back-end which is run on the RPi and was written in Python.

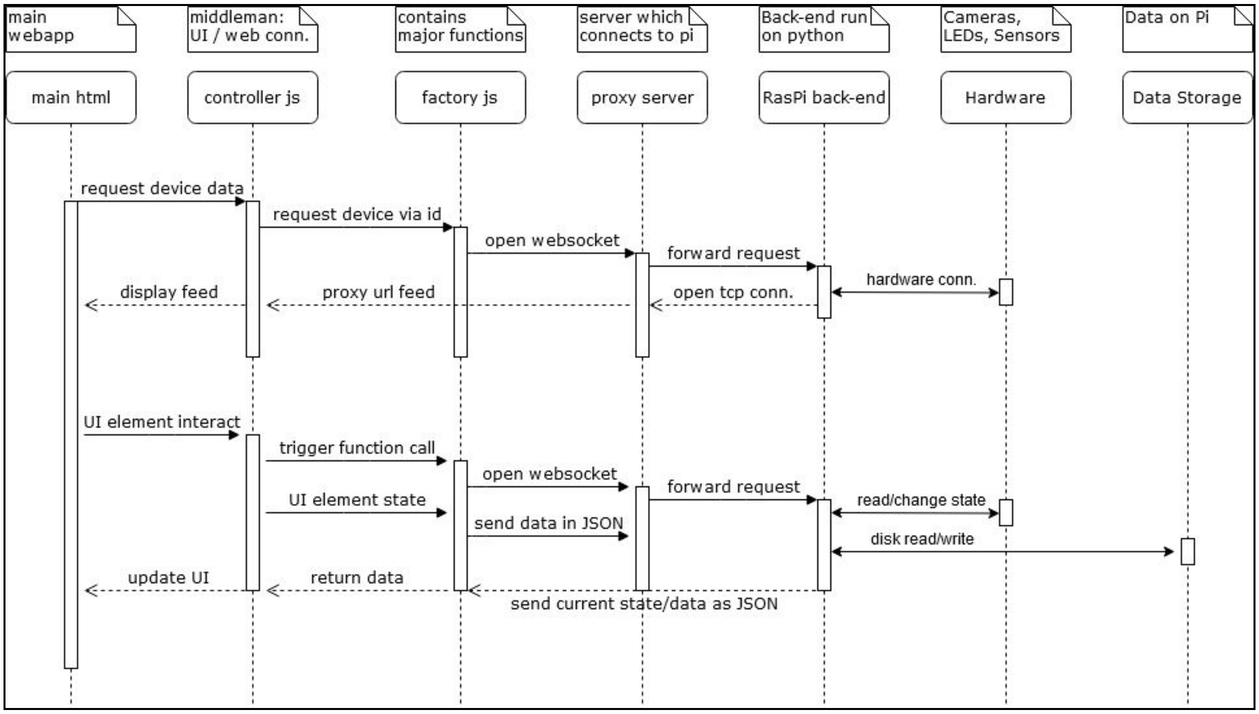

Figure 5: A UML diagram showing generally how the code works.

Assessment of Learning Impact

Student impact from workshops or laboratory exercises has traditionally been assessed largely in three ways. The first is by observing student performance as they complete a set series of tasks. Students are given instructions to complete laboratory experiments, to collect data, to operate equipment, etc. and are assessed by how well they performed the tasks and interpreted their data. The second method is to use standard tools for determining mastery, such as tests or quizzes, that are administered either before the students perform laboratory tasks, after students perform the tasks, or both. A pre-test/post-test comparison can be used to evaluate the gains in practical knowledge students acquire from the lab experience. Third, students can be compelled to engage in self-reflection by using survey tools to ask how they view their own learning.

There are several research questions that an analysis of student performance may answer, but perhaps the first avenue to explore is a relative comparison between two identical laboratory experiences, one conducted live and the other conducted remotely. Students who complete on-line labs from some remote location obviously cannot be observed directly as they undertake any assigned laboratory exercises. Their completed work, such as data analysis or conclusions however, can indeed be assessed.

The rig from Figure 4 is designed to allow students to measure pressure, temperature, and flow rate over time at various locations. The apparatus is designed to allow students to gain understanding of the behavior of water and other fluids by analyzing its thermodynamic properties. Students can also observe the motion of the water and the operation of the pump and measurement devices through the cameras. The apparatus was also designed to be used in conjunction with an undergraduate thermodynamics course. This course is optimized for and offered to non-mechanical engineering students. The class is offered each semester in two sections. Once section is a traditional course where students attend class in person and the other section is web-based where students are not required to attend but watch the lecture videos on-line as they are recorded. Both sections submit coursework solely online, except for semester exams which can be administered either live or online depending on the location of students in the web section. The enrollment is between 30 and 50 students per semester in each of the two sections.

A parallel study will be conducted where students in the live section of the course are required to perform a laboratory exercise in person. Students in the web section of the course will be required to complete the laboratory exercise online. Each student will be required to complete a pre-quiz to create a baseline assessment of their understanding of fluid properties before undertaking the lab exercise, will complete guided instructions during the lab exercise, and will complete a post-quiz afterwards. Students will also complete a survey which will be used to assess their own interpretation of the exercises impact on their learning, interest, motivation, and retention.This data collection will be done over numerous semesters to create a large ensemble of samples to produce more statistically significant results.

Conclusions and Future Work

Laboratory or hands-on experiences play a vital role in the education of engineers regardless of how much technology changes or advances and regardless of how education is delivered. As more high-level instruction is moved online, this should not suggest that historical means of delivering learning experiences should die out, they should evolve. So is the case for laboratory experiments, laboratory-based courses, hands-on activities, in-class demonstrations and the like. While moving such tools online will inevitably change the way that students experience them, the evolution is natural and warranted. To facilitate the conversion of simple laboratory systems to a remotely accessible interface the network infrastructure to do so must be as simple as possible, secure, inexpensive, composed of common components, easily scalable, and the software to run it must be freely accessible to educators.

Further work that is required to streamline the current infrastructure falls into several categories. First, the interface between the RPi, or host machine, to the physical laboratory equipment needs to be discussed. Much work was conducted on building custom circuits to interact with on/off switches, power sources, and a host of lab equipment from thermocouples to water pumps. Best practices for how to easily construct such interfaces must still be developed and documented.

Second, the current system is successfully scalable but only up to a point. Multiple video feeds alone quickly run up against the capabilities of the RPi 3. Stress testing on the ability of the local communication hardware to handle larger numbers of peripherals must be conducted and data collected on throughput, network load and video quality.

Last, the efficacy of online laboratories as an impactful student experience has limited coverage in the literature. Assessing student learning must be accomplished from the perspective of comparing practical, live laboratory exercises with their on-line, remote alternatives. As digital experiences engage more students in new ways, those new ways can be applied to education, but they must be built well. There is very little information available concerning best practices in implementing on-line labs as few educators develop or use them. This work seeks to add to that library of best practices.

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