Remote Laboratory for Machine Learning Training of a Soft Actuator's Control: A Case Study

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Abstract

The COVID-19 pandemic continues to pose difficult challenges for engineering laboratory research. Practicing social distancing in a lab is often difficult, and as universities move academic activities online, some research labs may be affected and even shut down. This paper studies the remote laboratory implementation that a student research group developed for testing material properties and machine-learning control of a dielectric elastomer actuator (DEA). This paper will present the remote laboratory setup, detail the remote lab's operations, and discuss results from remote experiments. Since remote lab operations are essential for the "Industry 4.0" and the "Engineering Education 4.0" that accompanies it, the case study will provide insights that educators and researchers can use in designing responsive remote labs.

Keywords

Remote laboratory, COVID-19, Industry 4.0, computational notebooks.

Introduction

The spread of COVID-19 across the world has abruptly forced engineering educators to react swiftly to maintain learning transactions. Since some engineering learning outcomes require experiential activities, engineering educators and students – as well as others in science, technology, engineering, arts, and mathematics (STEAM) fields – are facing implementation challenges during the pandemic. Remote laboratories (RLs) connect students with physical instrumentation in another location. They are not necessarily virtual labs, where students run simulated experiments in a virtual reality environment.[1] Rather, RLs seek to give students access to the essential interfaces for accomplishing useful lab work from a distance. This paper studies the methods and implications of a student-designed remote lab instituted during the midst of the pandemic in the United States.

The importance of remote learning extends far beyond the present pandemic. Massive open online courses (MOOCs), which implement a modern flipped classroom model, attract students from all across the world. Courses in engineering mechanics,[2] control systems,[3] and operations research[4] have been offered via MOOC platforms. The Swiss Federal Institute of Technology Lausanne (EPFL), has incorporated MOOCs and flipped classrooms into regular undergraduate education.[3] However, the effectiveness of RLs in engineering education is not yet well-understood, even though students are generally enthusiastic about them.[5] Preserving the quality of the hands-on experirence – and succesfully scaling a hands-on experience for many simultaneous learners – is critical for successful remote education,[6,7] and the pandemic has illustrated how engineering educators need robust and general solutions for remote laboratory experiments.

Long before COVID-19 hit, however, visionaries in industry had emphasized remote cyberphysical infrastructure like RLs. Since its inception in 2011, the fourth Industrial Revolution ("Industry 4.0") emphasizes the "fusion of the digital, biological, and physical worlds."[8] As such, it strives toward intelligence, autonomy, and decentralization in manufacturing and operations.[9] To accomplish these goals, the "Industry 4.0" integrates cloud computing and data-driven technologies to make industry more flexible and responsive.[10] Indeed, the Internet of Things (IoT) has provided bountiful opportunities for remote interactions with instrumentation, and an RL can be can be run with just a single-board computer (e.g. Rasberry Pi).[11]

From 2011 to 2016, the German education authority sponsored universities in the Excellent Teaching and Learning in Engineering Science (ELLI) initiative.[12] Each university worked in a unit of "Engineering Education 4.0" – a response to the modern requirements of the Internet-connected "Industry 4.0." Since the ideals of modern industry require a strong cyberphysical infrastructure, remote and virtual labs formed a core study area for this project. Some educational theorists are concerned that widely-implemented RLs will lock students into a single linear procedure, rather than allowing them the freedom essential for learning.[6] The German researchers, however, developed an architecture for tensile tests that permited efficient student access but still allowed students individual time to formulate their own questions and investigate independently.[1]

A successful RL must be highly available, concurrent, cost-efficient, and resilient (fail-safe).[11] In addition, an RL must reliably translate commands from the remote user to the physical instruments, within some acceptable tolerance. Figure 1 illustrates these essential components. For many years, National Laboratories' LabVIEW (Laboratory Virtual Instrument Engineering Workbench), was the leading commercial digital laboratory solution. As open-source tools – like Python packages for data acquisition (DAQ) – have proliferated, however, the cost and closed ecosystem of LabVIEW have become less appealing.[13] Thus, even though there are proprietary process control and automation tools, newer and more agile projects can start more quickly with modular, off-the-shelf free software. Thus, remote laboratory consortia have flourished in recent years.

Since 2002, the Univeristy of South Austrailia has maintained the NetLab system – an open-access and time-shared system – that it uses for education in several engineering disiplines.[14] Supported by government education grants, NetLab has found application in undergraduate and doctoral education across such countries as Sri Lanka, Poland, Singapore and Sweden.[14, 15] The NetLab emphasizes a centralized physical infrastructure, but the WebLab-Deusto – developed at the Univeristy of Deusto in Spain – presents a federated laboratory framework that has found use in Brazil and eastern Europe. The LabsLand product, a spin-off from the WebLab-Deusto, aims to bring RL technology to biology and chemistry fields and interoperate well with other frameworks. The Laborem project, based upon a Python framework, also includes learning manegement system integration and educational tutorial functions,[16] while the Massachusetts Institute of Technology (MIT)'s defunct iLab project provided a more user-directed access to live instruments.[17]

However, these ad-hoc RL infrastructures often do not find wide use beyond their universities of origin,[18] and are often tailored to specific disciplines.[19] Thus, even when they achieve the four fundamentals, these tools do not gain widespread acceptance. These papers often describe a full-stack Web service design, which indicates that they could be reinventing the wheel rather than

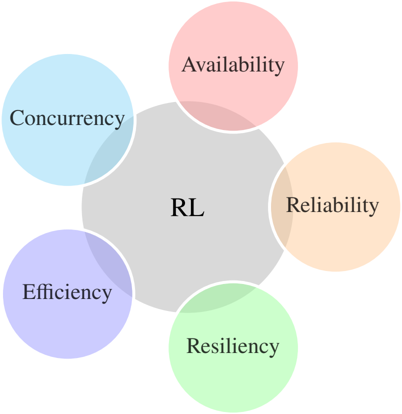


Figure 1: Components of a successful RL

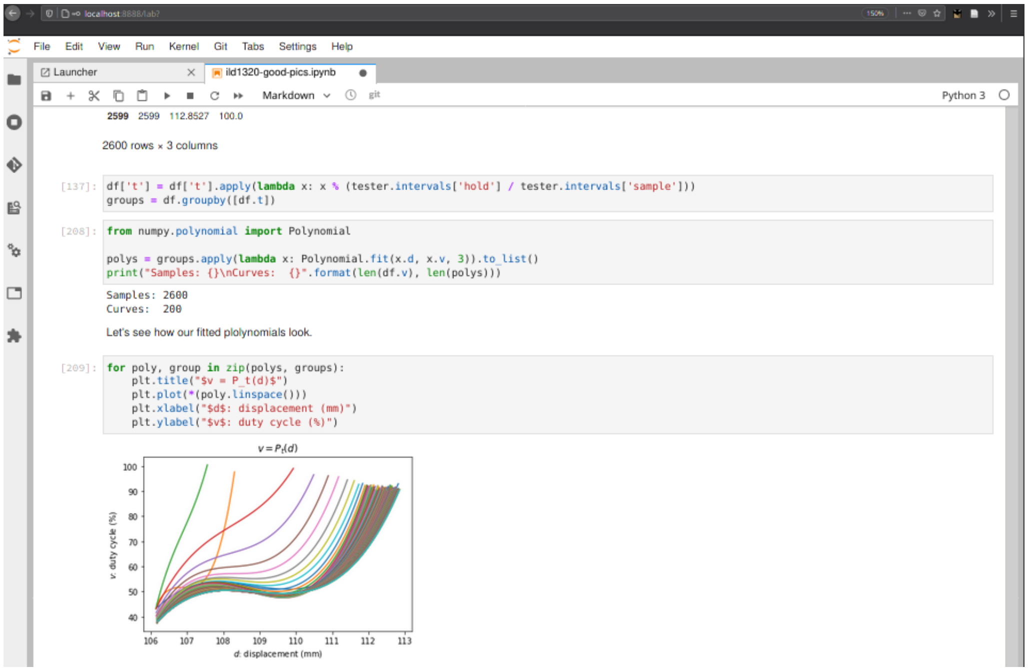
harnessing previously developed strategies. Each platform has different goals for education and thus fits into a different niche.

The COVID-19 pandemic caught everyone off guard, and educators quickly needed modular, interoperable laboratory solutions to continue teaching well. There was not time to carefully vet the complex solutions, like those above, that have that have developed. In the pandemic, educators have been forced to return to the four fundamentals of remote labs. Both engineering educators and resaerch scientists can benefit from greater access to customizable and stable tools for interacting with remote instrumentation. Previously documented responses to the pandemic have focused on virtual labs or have documented changes their educational approaches to match a remote setting.[20] Other groups have manufactured open-source all-in-one platforms, like the Open University of Catalonia's hardware platform Lab@Home.[21] This paper does not discuss these approaches. These discussions have emphasized the changes of approach required to continue providing quality engineering education at a distance, but this paper describes a specific approach implemented to keep laboratory workflows as consonant as possible with pre-pandemic workflows. Rather than designing a new framework, the students documented here performed minimal customizations on an existing solution – the Project Jupyter platform – to suit their needs during the urgency of the early pandemic.

Methods: Using JupyterLab for Remote Research

Before the pandemic struck, an undergraduate mechatronics research team was studying the material properties of dielectric elastomers and experimenting with a controller using Q-learning.[22,23] Such experiments required many hours of online experiemental time. Digital commands sent to an ESP-32 microcontroller controlled the pulse-width modulation (PWM) of signal sent to the elastomer. The elastomer's actuation was measured with an optoNCDT 1320 laser distance sensor. Both external interfaces – the ESP-32 and the laser optical sensor – connected to the host computer with standard UART-to-USB connections. Code was shared among the collaborators via GitLab.

One student researcher maintained access to the lab, but other researchers were not permitted inside as the nature of the laboratory room, about 12' by 8', would have made social distancing quite



```
2599   2599   112.8527   100.0

2600 rows × 3 columns
```

```
[137]: df['t'] = df['t'].apply(lambda x: x % (tester.intervals['hold'] / tester.intervals['sample']))
       groups = df.groupby([df.t])
```

```
[208]: from numpy.polynomial import Polynomial

       polys = groups.apply(lambda x: Polynomial.fit(x.d, x.v, 3)).to_list()
       print("Samples: {}\nCurves:  {}".format(len(df.v), len(polys)))
```

```
Samples: 2600
Curves:  200
```

Let's see how our fitted plolynomials look.

```
[209]: for poly, group in zip(polys, groups):
           plt.title("$v = P_t(d)$")
           plt.plot(*(poly.linspace()))
           plt.xlabel("$d$: displacement (mm)")
           plt.ylabel("$v$: duty cycle (%)")
```

Figure 2: JupyterLab computational notebook interface

difficult. To continue collaboration over the pandemic, the students first set up a virtual private network (VPN) to permit secure access to the laboratory computer from off campus. Although the PiVPN software was designed to run a lightweight VPN on a Raspberry Pi,[24] minimal modifications were required to establish a VPN on a stock Ubuntu Linux installation. Once connected to the VPN, the student researchers first tried screen-sharing with the laboratory computer via virtual network computing (VNC). Configuring VNC for the students' unusual use case proved time-consuming, and the connection still ran quite slowly after manual tuning. Moreover, without the added drain of creating separate desktop environments for each user, only one student could control the virtual desktop at a time. A solution to the aforementioned problem was found using the so-called JupyterLab. Some technical aspects of JupyterLab are outlined in the succeeding paragraphs.

JupyterLab is an open-source scientific computing product from Project Jupyter.[25] The product, first released in 2018, is a next-generation iteration of the Jupyter Notebook suite. The project aims to bring interactive computing and reproducible research through computational notebooks (Jupyter notebooks) – files that blend arbitrary code and visualizations and typesetting together into one flow.[26] Figure 2 shows a JupyterLab instance in active use for research. JupyterLab consists of kernels that provide interactivity with a given interpreted programming language – such as Julia, Python, and R – and a clean Web interface for editing and executing modular code.

JupyterLab presents itself as a local Web interface and runs its kernels on the local machine. However, its server can also be exposed across the local network, and other users can access the interface like they would any other webpage. Discovering this fact was the significant idea behind the students' remote lab implementation. Figure 3 shows the architecture of this remote laboratory setup. JupyterLab provides a token-based authentication service, but since the students already

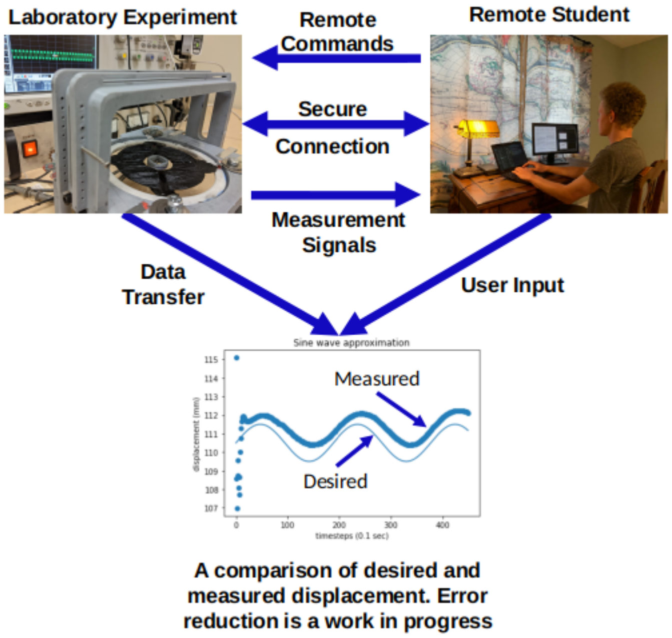


Figure 3: Cyberphysical infrastructure of RL

shared the server over a controlled and secured VPN they did not need to worry about authentication; everyone who had been given keys to the VPN was already trusted. Moreover, since the software runs in a Web browser, users on Windows can access Unix-based resources with no compatibility difficulties.

Discussion

Recall again the five criteria for a successful remote lab: availability, concurrency, cost-efficiency, resiliency, and reliability. The students expended no money, because they only used open-source software. JupyterLab itself required little time spent for configuration. Once they determined the architecture, the setup was quick and only used existing parts. The JupyterLab scheme proved quite stable and served the research group's needs for summer research during the pandemic. The students did not have the budget to procure proprietary software, develop their own scheme, or commit to the learning curve of a smaller open-source platform. Since the students ran the lab VPN themselves, they ensured consistent availability of the service with minimal technology. Moreover, the JupyterLab server places little overhead on the server – far less than the other forms of sharing tried – and so resources are maximally conserved for computations. To ensure resiliency and reliability, the students emphasized strong exception handlers around power controller code. Running over a self-hosted VPN also ensured network security, and hence reliability. Note also that the students' remote lab setup was not designed to be autonomous; it was designed so that collaborative research could continue when social distancing requirements permitted only one student to be physically present in the lab. The JupyterLab solution mentioned in the previous section permitted the student in the lab to have control over a session of the laboratory computer, while other students worked in the background. Thus, although only one test could be run on the physical elastomer at a time, the JupyterLab architecture could easily be generalized to a scheduling server and multiple lab computers – the basic topology that MIT's iLab used.[17] The JupyterHub software, also provided by Project Jupyter, provides a concurrent interface to JupyterLab resources.[27]

JupyterLab emphasizes the openness, interoperability, and stability requisite for "Industry 4.0," and has thus become an essential education and research tool. In 2015, there were 200,000 public Jupyter notebooks on GitHub; by late 2018, after the release of JupyterLab, the count had soared to 2.5 million.[28] There is even a popular Jupyter notebook to estimate the number of Jupyter notebooks published on GitHub. As an open-source product, the Project Jupyter platform is designed with extensibility in mind. The thriving community of developers and contributors have written domain-specific extensions to help process and visualize data in such fields as cognitive research[28] and robot operations manegement.[29] A notebook-based educational lab can also connect with a learning management system to evaluate submissions, and an `nbgrader` extension already exists for this purpose.[30] As an important point for interoperability, notebook kernels also exist for proprietary products like MATLAB and Wolfram Mathematica. Thus, to adopt modern RL techniques, research labs would not be required to shift their workflows to open-source languages.

There have been a few examples of the transition we are describing here.The well-established VISPA (Visual Physics Analysis) platform has begun migrating from an in-house server architecture to the flexibility provided by JupyterLab.[31] Analyzing a mature project's migration to JupyterLab also illustrates the limitations of the current Project Jupyter architecture – particularly relating to scalability and security – and how these may be addresed. VISPA's experience provides evidence that Project Jupyter's products – including JupyterLab – present a mature format and interface for collaborative scientific computing. The Delft Univeristy of Technology (Netherlands) has recently piloted a JupyterLab-based sophisticated RL for a graduate-level electronics course,[32] but to date the authors have not seen any other published implementations that harness the unique educational advantages of JupyterLab for remote laboratory work. We conclude that JupyterLab can help relieve developers from the burden of developing low-level proprietary interfaces for their research products.

A Note on Resilience

In the context of how humans (especially adults) respond to loss, violent or life-treathening events, the concept of resilience refers the stable trajectory of mental health state of a person exposed to the aforementioned stressors.[33] What, perhaps, makes COVID-19 an unusual stressor is the combination of scale (worldwide), duration (almost a year currently), and multi-domain (economic, educational, social, political) impacts, among other characteristics. It is perhaps too early to produce significant studies on the post-traumatic effects of the current pandemic, since some of them may occur several months after the severe event.[33] (In China, for example, several nationwide studies have reported depression and anxiety symptoms among Chinese people during the COVID-19 pandemic.[34, 35]) With regard to higher education, a global study conducted with a cohort of more than 30,000 students from 62 countries[36] found the following:

- The perception of a greater workload and the constraints of inadequate computer skills prevented students from perceiving their own improved performance in the new teaching environment.

- Students expressed concerns about their future career and studies.
- Students seemed to experience a combination of boredom, anxiety, and frustration.

Furthermore, in a report reproduced by the American Society for Engineering Education (ASEE),[37] 67% of faculty respondents mentioned that they had "re-designed lab activities for online instruction during spring semester" of 2020. A common voice was that simulating a practical activity did not produce the same understanding as physically performing it. It was also reported that many laboratories experiences were completely canceled. Furthermore, among research staff and students, the stressors were even higher. The most affected were institutions with wet labs and high-performance computer facilities. However, research has shown that when given enough time most people can be resilient even when confronting extreme life situations.[38] The student researchers involved in the current work found a way to not only bring a positive spin to the pandemic situation, but also of producing a tool to continue to collect research data during the most acute time.

Conclusions and Future Work

The techniques of RLs are an essential foundation for "Industry 4.0" – and the "Engineering Education 4.0" that accompanies it. The COVID-19 pandemic has given engineering educators unexpected opportunities to innovate their approaches to laboratory instruction and research. In the early throes of the pandemic, the authors developed a RL framework that relies upon computational notebooks to address the four fundamental requirements. Rather than developing new infrastructures from scratch, educators and researchers can also build their laboratories on the same collaborative solution.

A prime avenue for future research is integrating JupyterLab's flexibility with tutorial-based learning systems. Widespread implementations based on JupyterLab could enable more robust studies of RL effectiveness for problem-oriented engineering education and interdisciplinary integration – both key components of "Engineering Education 4.0."[6] Previously-mentioned groups have designed ground-up graphical interfaces for their lab tutorials, but much of the same user-friendliness could perhaps be had in much less time with a notebook-based tutorial. Remote labs have already shown promise for augmenting interactivity in massive open online courses (MOOCs).[1] Extending the computational notebook model to a large remote lab infrastructure would bring together two important strands of "Industry 4.0" for education.

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