2023

Experience With Remote Laboratories For On-Campus Engineering Degrees

David P. REID
The University of Edinburgh, United Kingdom, s0967663@ed.ac.uk

Timothy D. DRYSDALE
The University of Edinburgh, United Kingdom, timothy.drysdale@ed.ac.uk

EXPERIENCE WITH REMOTE LABORATORIES FOR ON-CAMPUS ENGINEERING DEGREES

DP Reid
School of Engineering, University of Edinburgh
Edinburgh, UK
0000-0001-6234-1298

TD Drysdale[1]
School of Engineering, University of Edinburgh
Edinburgh, UK
0000-0003-3068-2113

Conference Key Areas:
Virtual and Remote education in a post Covid world
Innovative Teaching and Learning Methods

Keywords: *remote labs, practical work, non-traditional practical work*

ABSTRACT

Remote laboratories extend the teaching and learning opportunities available for on-campus courses, by increasing the overall capacity for practical work and enabling new types of activities. We present three case studies from different types of usage within the School of Engineering at the University of Edinburgh over the last three academic years. Each case study provides an overview of the experimental hardware and user interface, the learning context and reflections on their development from our perspective as providers of the system. The case studies include a pendulum lab that provided large cohorts of students access to lab equipment in a traditional classroom setting with in-person peer-to-peer and peer-to-staff interactions, but with remote equipment; a truss lab that was used to provide live lecture demonstrations and real-world data for tutorial questions ; and a spinning disk lab that allowed students to complete assessed coursework during the Covid-19 pandemic. Our remote laboratories have been successfully used under both pandemic and post-pandemic conditions, with ongoing usage growing. The software and hardware is open-source so as to enable adoption by a wider community of users.

[1] *Corresponding Author*

TD Drysdale

Timothy.Drysdale@ed.ac.uk

1 INTRODUCTION

Many traditional university campuses continue to face pressures from increasing student numbers, with the amount of in-person laboratory work limited by the available physical space. A continued perception of a skills gap in UK engineering graduates (Armitage & Bourne, 2020) indicates there may be significant value in expanding the amount and type of practical work available to support students in their learning. In other subjects, it has been shown that graduates valued more highly those educational tasks that most closely represented aspects of their professional practice (Wood et al., 2015). Furthermore, the Covid-19 pandemic has raised global awareness of the value of diversity in working modes and patterns, such as by making education remotely accessible (Graham, 2022). An aspect of education that is non-trivial to deliver remotely is practical work, due to the technical complexity of the underlying infrastructure required to deliver at scale. However, the drivers above have contributed to a renewed consideration of remote laboratories for traditional campuses (Drysdale et al., 2020).

Remote laboratories consist of real hardware accessed and controlled via a web browser. They provide the opportunity for students to attempt practical work from any (internet connected) location at any time and have been shown to provide positive learning outcomes for students (Post et al., 2019). Remote lab hardware can be physically located in spaces not normally associated with practical work, such as public foyers in campus buildings, where multiple copies of the hardware can be efficiently installed. In this way the aesthetics of the public spaces and visibility of institutional activities are increased, all without taking up limited teaching laboratory space. Remote laboratories have been shown to have advantages over simulated labs, with students reporting increased trust in data, motivation and perception of the veracity of the experience when using remote laboratories (Jona et al., 2011) and learning outcomes are better (Corter et al., 2011). Engineering students also need to understand how real-world factors add noise and variability to their data and this natural variability enables the type of authentic inquiry that is missing in simulated labs, even when variability is programmed in (Jona et al., 2011). Although remote laboratories remove the hands-on manipulation of physical hardware, the learning intentions of engineering labs cover a wide range of skills, including data analysis, comparison to theory and communication (Feisel & Rosa, 2005), and students report ‘no significant difference’ or ‘easier with a remote lab’ for demonstrating the majority of lab skills (Reid et al., 2022). When learning intentions are specifically focused on psychomotor skills then a traditional lab format should be used; however, direct manipulation of hardware is not a necessary condition for the development of other practical skills (see Brinson, 2015).

The School of Engineering at the University of Edinburgh has begun embedding remote labs in its on-campus degree programmes, using the *practable.io (Drysdale et al., n.d.)* remote lab infrastructure being developed there. The *practable.io* infrastructure has been described in (Reid et al., 2022) and is available open-source in order to encourage the adoption, and ease the burden of development, of remote labs at other institutions.

The remainder of this paper describes three case studies that provide details of specific remote lab implementations and how they have been used to meet a teaching and learning need that would be difficult with traditional, in-person access to practical hardware. This includes how traditional classroom spaces can be used for practical lessons (case study 1); how remote access to equipment provides opportunities for live data collection during lectures and tutorials (case study 2); and how assessed coursework was possible during the Covid-19 pandemic (case study 3).

2 METHODOLOGY

We present case studies exploring three different ways in which remote labs can be integrated into on-campus degree courses. These case studies are presented from our perspective as providers of the remote laboratory facilities. The teaching exercises were developed by course organisers and teaching staff. Each case study focuses on a single remote laboratory exercise and includes:

- an overview of the experiment
- a description of the learning context
- a reflection on the development process

3 RESULTS

3.1 Case study 1: Pendulum lab (in-person, in classroom)

The pendulum lab (Fig. 1) consists of an electromagnetically driven pendulum and an encoder for measuring angular position. Students are able to control the driving amplitude, braking strength, sampling rate and can compare forced braking (‘brake’ mode) with self-induced loading of the coil (‘load’) and free, natural decay (‘free’). Pendulums allow students to investigate many aspects of periodic motion, including: variations in period with amplitude, exponential decay parameters, how sampling rate affects measurements, and how the remote lab pendulum compares to periodic motion theory. Students are also able to make ‘analogue’ measurements of the pendulum using on screen ruler and protractor tools (see Fig. 1). A scale placed in the webcam view allows students to manually calibrate the ruler tool to make accurate measurements of objects in the webcam view.

Our pendulum labs provided experimental measurement and uncertainty activities to a large (450-student) first year course, without needing dedicated laboratory space. Students were located in traditional classrooms and accessed the remote hardware via their own laptops on the university’s Wi-Fi network. A series of sessions over two days allowed all students to access the practical work, with parallel sessions resulting in approximately 60 connections to the remote lab system at any one time. We repeated this in two different weeks focusing on different aspects of the task.

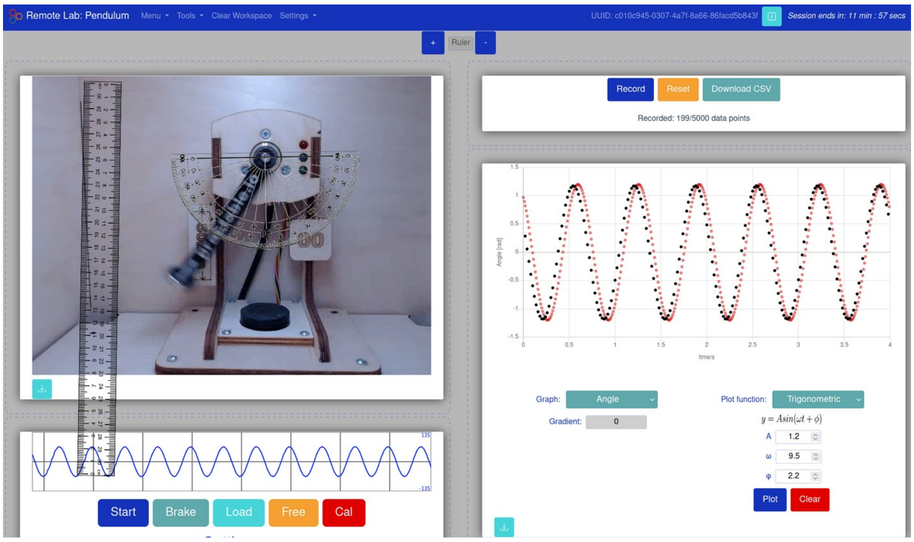

Fig. 1. User interface for the pendulum remote lab, showing webcam view, analogue measuring tools and graphing components.

The students also had access to the spinning disk lab, described in the third case study. We had already designed the pendulum experiment as a demonstrator for the concept of remote laboratories and for use in open days for outreach. After showing the course staff the experiment they iteratively developed a set of tasks that would suit the educational goals of the course. Now that the course team have successfully delivered this experience at a large scale we are working together on developing new hardware to create an additional experiment.

Figure 2 shows how pendulum and spinner remote lab usage varied across the hours of the day. Data was collected between 02/03/2023 and 19/06/2023, which includes the second week of the sessions described above. These sessions ran between the hours of 14:00 and 18:00, hence the peak in access across those hours. However, a major benefit of remote access to hardware is evident in the extension of lab usage outside of usual university working hours. The insert in Figure 2 shows the different operating systems used to access the remote labs during this same period. Desktop/laptop connections (Windows, Mac, Linux and ChromeOS) make up the vast majority of connections; however, the user interfaces have been designed to accommodate mobile usage (Android, iPhone, iPad) as well.

3.2 Case study 2: Truss lab (lecture demonstrations, tutorials & assignments)

Our truss remote lab (Fig. 3) consists of a six-member truss with each beam having a full-bridge strain gauge arrangement using two biaxial strain gauges and a linear servo to produce a load force on the truss. Users have control over the load (within safe limits) by positioning the servo and can tare the strain gauges and load cell. Data is displayed on the user interface as an overlay on an image of the truss, with values in micro-strain ($\mu\varepsilon$) for gauge measurements and as a force (N) for the load cell. Users can also capture a snapshot of all measurements in a table, graph different permutations of gauge and load cell data, and display theoretical strain measurements based on the measured load force. A set of eight truss experiments were prepared.

A structural mechanics course was looking for the opportunity to provide students with live demonstrations and data for calculations during lectures and tutorials. In a previous iteration of the course, before remote labs were available, students only had access to a single truss in a teaching laboratory. They would physically load the truss and take measurements from a digital interface. With only a single truss available, throughput was limited and it could not be demonstrated during lectures due to the difficulty in transporting it.

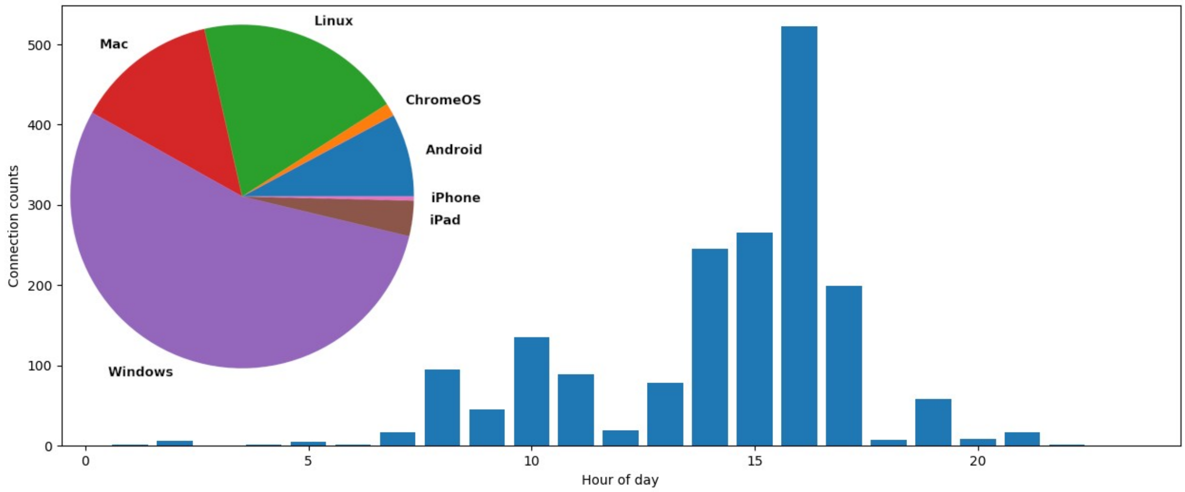

Fig. 2. Usage data across the hours of the day for the pendulum and spinner labs between March and June 2023. Insert shows the operating systems that users are accessing the labs from.

With adoption of the remote lab version, the trusses could be demonstrated live in lecture theatres to show the real-time behaviour of the beams when loaded. During tutorial sessions in traditional classroom settings, students were given access for 10 minutes (extended if necessary) to one of eight trusses to collect strain data for a set position of the load mechanism. They were then asked to calculate the load force that would produce those strain results. During classroom use of the truss lab, the UI did not reveal load forces or theoretical comparison values. After calculations were performed and submitted, students were given access to the fully featured UI so that they could explore the lab further in their own time. Rather than using the same fixed example dataset for all students, remote access to real experimental setups provide the opportunity for students to utilise live data for calculations, with the potential for multiple, unique hardware setups to produce variation in students' collected data. For example, we have additional truss experiments awaiting construction using different beam materials.

Through careful design of the user interface, remote labs provide an opportunity to scaffold a student's interaction with the hardware based on the context and learning intentions. For example, the UI can show data required for a calculation, but delay revealing the measured quantity that students are attempting to predict. We also developed UIs for other contexts, such as with potential university applicants during open day events. There we used a UI with an alternative control scheme that simplified the explanation given by the demonstrator. Timely development of new activities is made possible, in part, by the use of web app frameworks like Vue.js, where reactive UI components can be shared between remote lab implementations. The open-source license of our software also means that adopters are not tied into a specific lab configuration, allowing for re-design of firmware and user interfaces to suit local institutional requirements, if necessary.

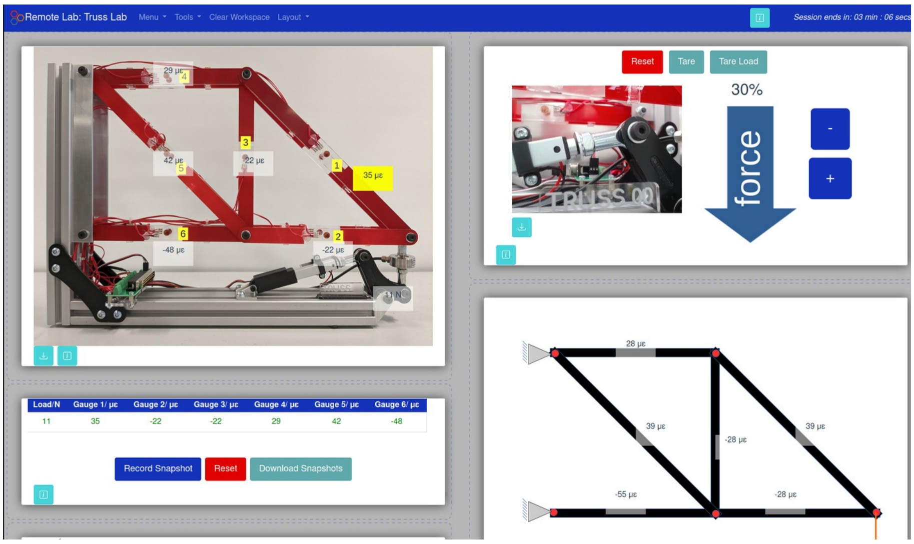

Fig. 3. Truss remote lab user interface in "open day" configuration, providing all data, simple control and theoretical comparison.

3.3 Case study 3: Spinning disk (individual asynchronous access)

The spinning disk remote lab was developed to allow students to investigate the application of proportional-integral-derivative (PID) controllers. These controllers are widely used in industry for controlling mechanical movement, regulating speed and managing the temperature of chemical processes. The principles are similar for each application so students can be taught them using any convenient type of hardware. The remote lab hardware comprises a brushed DC motor, optical encoder and a weighted disk that allows students to explore position control and speed control. The user interface allows students to configure the controller and run various position and speed control tasks of their own devising. There are limits encoded in the firmware to prevent potential damage from over-speed and excessive oscillations. To show students what is happening in the experiment, encoder data is collected every 5ms and sent for display on the user interface. Students can see and manipulate the data in multiple ways, using the data snapshot, table and graphing tools. The data can also be exported as a CSV file for analysis in external software, such as Excel or MATLAB. It is important for students to observe the effect of changing the angular inertia (size and weight) of the disk. This lab has a set of 12 differently dimensioned aluminium disks (4x each set in its current format making 48 spinner labs available), the details of which are provided to students via the webcam view. Students were assigned two different weighted disks for their assessed coursework.

The first use of the spinning disk lab for teaching and learning allowed control systems laboratory work to be conducted during the Covid-19 pandemic, when traditional lab work was not possible and students were restricted to locations outside of the university. Students were able to access the remote lab on any internet connected device via the browser, allowing students to complete assessed coursework with very few modifications to the in-person version of the lab. Beyond giving students access to the (likely) only practical work they had during the pandemic restrictions, the remote lab allowed 10-20x more experimental time for each student compared to the previous version of the lab in a traditional setting. Students reported that the ability to manage their own time during remote lab usage was a major advantage of the system (Reid et al., 2022).

Figure 4a shows the cumulative hours of student use of the spinning disk lab in the second year it ran (2022), reaching approximately 2500 hours for N ≈ 250 students, i.e. 10 hours per student. Previously, the in-person exercise offered three hours per student, in groups of six, for a total of 750 student-hours of experimentation, but only 125 student-hours of *one-to-one equivalent time* with the equipment. We arrive at the latter figure by dividing the total time by the group size. Hence the remote lab not only tripled the total student-hours, but increased the equivalent one-to-one time by a factor of 20. In some settings, group work is pedagogically motivated, while in others it is a result of resource limitations so a comparison of one-to-one equivalent time is appropriate. Since the time students spent on the remote labs was set by them, our data may indicate a significant gap between the supply and demand of laboratory time in traditional laboratory settings where resource constraints are a dominant factor. We also noted that students used a range of session lengths from the options available (Figure 4b). We only offered the 90 min session for the first two weeks, to manage demand, however this was unlikely to affect the popularity of the 5 min sessions, so we conclude that offering a range of session times is likely to better match student preferences. We are now also able to offer longer sessions again because in 2023 we implemented session cancellation.

Over the course of three years, feedback from student and staff usage has continually driven the development of this remote lab. Feedback has also led to the updating of our booking system from first come, first served to a system allowing for future booking, pre-booking for whole classes and cancellation of bookings (Reid & Drysdale, 2023) whilst maintaining a freely available pool of labs when they are not assigned to courses. We can also set the time intervals bookings can be made for and the number of concurrent pieces of hardware any single user can book.

Feedback from staff has highlighted the importance of testing hardware against the intended learning outcomes of the course. In the first academic year, we tried a number of different configurations for the weighted disk in an attempt to demonstrate all of the control theory principles required. Our first attempt used pennies as variable weights but the small slop necessary for making them removable introduced an unacceptable degree of non-linearity. Similarly, the friction in the original motor resulted in variability from run to run and obscured the steady state error that occurs depending on the type of input (step or ramp). In year 2 we upgraded the motors so that this large, compulsory Year 3 class could focus on understanding the ideal response with fewer complicating real-world factors. In our view, the original experiment design would be useful for a more advanced class where the introduction of real world, non-idealities is in the intended learning outcomes.

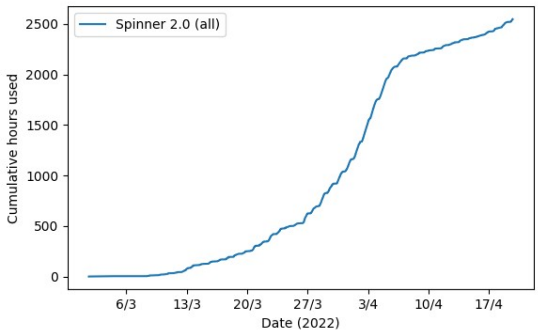

Fig. 4a. Spinning disk cumulative hours used between March and April 2022.

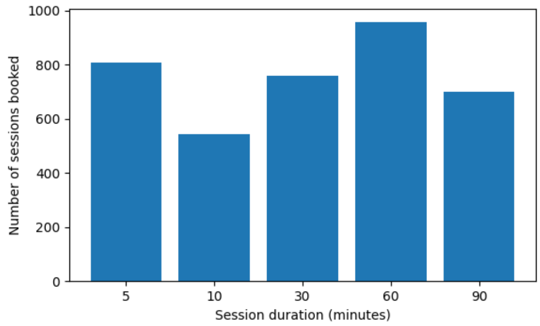

Fig. 4b. The number of sessions booked for each possible session duration (5, 10, 30, 60 and 90 mins).

4 SUMMARY AND ACKNOWLEDGMENTS

We have described three possible use cases of remote labs for engineering education, providing an insight into the unique opportunities afforded by the use of remote labs for on-campus degree programmes. We found that remote labs provide a complementary set of teaching and learning opportunities to in-person lab experiences, with remote labs enabling more time for student exploration of hardware; access to real equipment outside the space and time confines of the traditional lab setting; and an opportunity to help scaffold student learning through the re-mixing of user interfaces for specific contexts.

We are grateful to the following course organisers and staff for developing the teaching materials and co-developing the hardware and/or user interfaces: Jonathan Terry and Brian Peterson (case study 1), Thomas Reynolds and Marcelo Dias (case study 2), Aristides Kiprakis (case study 3), and Symon Podilchak and his research team (electromagnetics, to be the subject of a future publication). Michael Merlin proposed the pendulum control method. Andrew Brown designed the mechanical hardware and built the experiments together with Calum Melrose. Imogen Heard contributed to the electronics design. Additional essential support was provided from Technical, Buildings, IT, and Professional Services staff. The work was funded by the School of Engineering, University of Edinburgh. The remote lab infrastructure is open source and available at https://github.com/practable.

REFERENCES

[1] Armitage, L., & Bourne, M. (2020). *Engineering UK 2020 Educational pathways into engineering*.

[2] Wood, L. N., Psaros, J., French, E., & Lai, J. W. M. (2015). Learning experiences for the transition to professional work. *Cogent Business & Management*, *2*(1), 1042099.

[3] Graham, R. (2022). *Crisis and catalyst: The impact of COVID-19 on global practice in engineering education* (p. 98). https://www.rhgraham.org/reports/

[4] Drysdale, T. D., Kelley, S., Scott, A. M., Dishon, V., Weightman, A., Lewis, R. J., & Watts, S. (2020). Opinion piece: Non-traditional practical work for traditional campuses. *Higher Education Pedagogies*, *5*(1), 210–222.

[5] Post, L. S., Guo, P., Saab, N., & Admiraal, W. (2019). Effects of remote labs on cognitive, behavioral, and affective learning outcomes in higher education. *Computers & Education*, *140*, 103596. https://doi.org/10.1016/j.compedu.2019.103596

[6] Jona, K., Roque, R., Skolnik, J., Uttal, D., & Rapp, D. (2011). Are Remote Labs Worth the Cost? Insights From a Study of Student Perceptions of Remote Labs. *International Journal of Online and Biomedical Engineering (IJOE)*, *7*(2), 48. https://doi.org/10.3991/ijoe.v7i2.1394

[7] Corter, J. E., Esche, S. K., Chassapis, C., Ma, J., & Nickerson, J. V. (2011). Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. *Computers and Education*, *57*(3), 2054–2067. https://doi.org/10.1016/j.compedu.2011.04.009

[8] Feisel, L. D., & Rosa, A. J. (2005). The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education*, *94*(1), 121–130. https://doi.org/10.1002/j.2168-9830.2005.tb00833.x

[9] Reid, D., Burridge, J., Lowe, D., & Drysdale, T. (2022). Open-source remote laboratory experiments for controls engineering education. *International Journal of Mechanical Engineering Education*. https://doi.org/10.1177/03064190221081451

[10] Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, *87*, 218–237. https://doi.org/10.1016/j.compedu.2015.07.003

[11] Drysdale, T. D., Reid, D. P., Brown, A., & Heard, I. (n.d.). *Open-source digital infrastructure and hardware for remote laboratories in education*. practable.io. https://github.com/practable

[12] Reid, D. P., & Drysdale, T. D. (2023). Student perceptions influenced by remote laboratory infrastructure (in-press). *Proceedings of the 2023 6th Experiment@ International Conference (Expat'23)*. Experiment@ International Conference 2023, Portugal.