Remote Practicals in the Time of Coronavirus, a Multidisciplinary Approach

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Abstract

Due to the COVID-19 pandemic, universities across the world have curtailed face to face teaching. Associated with this is the halt to the delivery of the practical experience required of engineering students. The Multidisciplinary Engineering Education (MEE) team at The University of Sheffield have responded to this problem in an efficient and effective way by recording laboratory experiences and putting videos, quizzes and data online for students to engage with. The focus of this work was on ensuring all Learning Outcomes (LOs) for modules and courses were preserved. Naturally, practical skills cannot be easily provided using this approach, but it is an effective way of getting students to interact with real data, uncertainty and equipment which they cannot access directly.

A number of short case studies from across the range of engineering disciplines are provided to inspire and guide other educators in how they can move experiments on line in an efficient and effective manner.

No student feedback is available at the time of writing, but anecdotal evidence is that this approach is at least acceptable for students and a way of collecting future feedback is suggested. The effort expended on this approach and the artefacts produced will support student learning after the initial disruption of the lockdown has passed.

Introduction

With lockdowns implemented globally, and face to face teaching stopped, the way that most universities teach has been disrupted. Technology can effectively replace many forms of classroom experience. Flipped and blended learning modes are well established as approaches to teaching, and Zoom, Google Meet, Webex and Microsoft Teams allow reasonably effective face to face teaching to take place in live lectures and tutorials. The development of Virtual Learning Environments (VLEs) such as Canvas, Blackboard and Moodle allow the provision of teaching material and assessment to take place. However, in engineering and the sciences there is the need for students also to conduct practical work. Sometimes this requires specialist, large equipment or risky activities. This paper discusses and gives examples of various innovative ways of moving practical activities from face-to-face to virtual delivery.

Multidisciplinary Engineering Education (MEE) is a specialist department at the University of Sheffield which is dedicated to delivering practical teaching for all students in the Faculty of Engineering using large, shared laboratories and workshops. MEE consists of around 50 staff, including 30 teaching technicians and 15 academic staff, each of whom is responsible for delivering a themed area of practical learning. In addition to this, MEE employs more than 200 PhD students as graduate teaching assistants (GTAs), to support learning, supervise students and assist in marking. Due to the ubiquity of some basic engineering principles, some practical activities are provided to 1000 students a year across 7 different programmes. This economy of scale and concentration of practical teaching expertise has made for an excellent student experience. The scale of the operation requires a large supporting infrastructure including 5 administrators to lead on timetabling, data management, lab book production and student experience.

From MEE's inception in 2015 we have worked with departments in the Faculty of Engineering to integrate practical teaching seamlessly into their courses, usually delivering practical learning to an entire cohort when subjects are introduced by the lecturer. We are generally able to deliver an identical experimental activity to up to 320 students within the same week because of the scale of our laboratories. Our 5 largest laboratories can all accommodate between 80 and 144 students simultaneously.

MEE is dedicated to the delivery of practical teaching and as a result we carefully consider how to ensure laboratory teaching is as effective as possible[1]. We have adopted a blended learning approach for all our experiments. Figure 1 shows all 5 steps in the design and implementation of remote practicals, of which the central 3 elements are core to all of our practical activities:

- **The pre lab**. This element is delivered online using the VLE and prepares the student for the experiment. As a minimum, it contains the theory and the learning outcomes, information and often videos on the equipment and its use, and the Health and Safety precautions. The pre lab will also contain quizzes to ensure that the students have read and understood the content. As this is universal across all of our laboratories, we are able to employ a consistent policy of refusing entry to students who have not completed the pre lab requisites.
- **The lab**. Here students actually perform practical work. The time spent in the lab is optimised, as an understanding of the theory behind the practical and what they are required to do has been provided in the pre lab. This saving of valuable laboratory time has allowed us to integrate more experiments into our courses, so students experience a larger variety of practical activities.
- **The post lab**. This element ensures that students have engaged with the exercise and are able to reflect on it. It could be a quiz, a report or a piece of work integrating ideas across a number of experiments. Often there is no need to

assess the lab summatively, as it is integrated into and thus tested in the associated course assessments.

1 **Preparation for online labs**

Video to explain expectations and ground rules for online labs, followed by multiple choice test. 100% required to gain access to online materials. Students then complete activities at own pace

2 **Pre-lab**

Develop and test understanding of key points from theory

3 **In-lab**

Data collection and presentation, analysis and uncertainties

4 **Post-lab**

Students perform calculations and short answer questions related to the application of these concepts in a science and engineering context

5 **Marking**

Calculated formula and numeric Blackboard functions used to minimise marking workload. Grade distribution analysed to compare with in-person labs and faculty guidelines

Figure 1: Process of virtual labs

Literature review

When moving practical teaching from face to face to remote teaching, three main approaches can be taken: simulation, remote control of equipment, and providing recordings of data and experiments. Some prior work has sought to contextualise this, but without implementing any form of teaching[2,3].

One of two early (2007) papers on remote laboratories explicitly describes three types of laboratory exercise[4].

(a) Development Lab, where students answer specific questions about a design and determine if a design performs as intended.
(b) Research Lab, generally an addition to the body of knowledge.

(c) Educational Lab, where students apply theoretical knowledge to gain practical experience.

The work also refers to the value of pre lab experiences and acknowledges that remote labs at that time could not replace all of the experience of a face to face laboratory.

The other (2006) early work on non-face-to-face laboratories is a literature review on the subject of “Hands-On, Simulated, and Remote Laboratories”[5]. They state that for many remote laboratories, the more effective the computer interface is, the easier the exercise is to move online.

Further work used remote controlled and internet enabled experiments to allow students to engage with real equipment and data while at a different location[6]. This approach had two advantages in that one set of equipment can serve many students, and that the experimental results are obtained from real equipment with noise and nonlinearities. A large scale piece of work on remote and virtual laboratories has been conducted in Germany on manufacturing and materials testing[7]. Labelled “Education 4.0”, it has increased student understanding and engagement, particularly for Massive Open Online Courses (MOOCs). They report that students who have conducted the remote practicals arrive for real laboratories far more prepared, much like MEE’s pre labs.

A group from Mexico and the UK have created a series of remote mechatronics and electrical laboratories, which can be controlled with data acquired remotely, using LabVIEW software via a webserver[8]. The work reported on three laboratories: an electropneumatic system, control of AC motors and residential wiring circuits. A small study of student feedback reported that students like the interface and can follow the experiments while lectures are being conducted.

A publication that looks at the effect of remote experiments on student learning comments that remote experiments work better for earlier years[9]. In addition, effective remote experiments are stated to integrate three elements: “The first was technical/technological, the second was administrative and the third academic.” The work also implies that remote experiments with good staff support are a useful element for inclusivity and accommodating a variety of learning styles.

A report on the Australian Labshare Project[10] looked at the student experience of a series of remote electronics and control laboratories shared between 6 universities. Their results show that students actually preferred the remote laboratories except for “Help and support if required”. In common with other literature, they report that staff support and engagement are key to student success. They also state that it may be required to have different Learning Objectives (LOs) for remote practicals than for conventional experiments. A further finding is that students do better on subsequent remote experiments than on their first one, implying an induction process may be useful.

Most of the work that has been found in the literature refers to electronics and control laboratories, but a consortium of universities has built a remote materials specimen testing lab which can be used by both staff and students[11].

Another approach that can be taken is asking students to perform a “take home lab”[12]. Here students use artifacts around them to engage with measurement and analysis. This can be a powerful aid to augmenting traditional teaching, but could have elements of risk unless students are carefully inducted.

From these examples, it can be seen that remote laboratories are becoming prevalent. However, they require a lot of time and effort to implement effectively. Additionally, most of the topics approached are from the electronics and control fields where computer interfaces are ubiquitous. At a time when conventional laboratories are suddenly not available, a quick fix without additional hardware modification is necessary. The work described here shows a large number of multidisciplinary approaches to moving the practical experience on line in a fast and efficient manner. These aim to preserve as much as possible of the original student experience.

General approach

At the University of Sheffield, the Faculty of Engineering teaches 4700 undergraduate and taught postgraduate students across 10 degree programmes. MEE is responsible for delivering over 2000 individual practical activity sessions comprising 600 different experiments to these students. Both the scale of the operation and the complexity of the service provision model requires effective infrastructure and robust communication channels to effectively function. This infrastructure includes:

- Appointed academic liaison staff to act as a point of contact and provide overarching management of sessions for each degree programme.
- A master spreadsheet, known as the Directory of Activities (DoA), which uniquely identifies and records metadata associated with all of our activities.
- A departmental timetable of all practical activities, linked to the DoA using unique identifiers, administered by a learning and teaching manager.

This infrastructure allowed the creation of a rigorous process to pivot to remote delivery, developed and agreed within 24 hours. A spreadsheet was produced from the timetable, containing a list of the 602 practicals still to be taught in 14 different laboratories. Through linking this spreadsheet to the DoA, metadata for each session was attached, including the MEE staff member responsible for the practical activity, and the module lead responsible for all teaching across the related module, including lectures, tutorials and assessment. Each member of staff responsible for an activity was tasked with finding the most appropriate teaching method to deliver the practical remotely, and asked to populate the spreadsheet with information about what was done and what impact this would have on assessment.

Having a single location for all this information allowed:

- Effective communication with the Faculty Learning and Teaching Committee, who report to the central University Learning and Teaching Committee. The information about the impact on assessment was particularly important to inform the University's policy on concessions for students due to the disruption.
- Effective liaison between departmental directors of learning and teaching, module leaders and module teaching staff, regarding the process we adopted for our teaching delivery, and for response to student queries.
- MEE management to audit completion of the move to remote practicals, and MEE administrative staff to respond to student queries without the need to involve academic staff.

As practical work is fully integrated into most Sheffield engineering courses and forms a key to students understanding and contextualising material, it was inadvisable to just remove the experiments. It was therefore decided that as a general approach we would replace the conventional lab sessions with an online delivery of the lab, using videos, data and/or quizzes to get the students to still deliver the required learning outcomes. Due to our experience in creating pre lab activities, this was a relatively small intellectual step, but in many cases required a huge amount of work to prepare and deliver. A number of other approaches were considered, such as abandoning the experiments, getting students to do this work at home, the remote operation of experiments from students' locations or the simple approach of just providing data for the students to process. Understanding that our response was reactive, we wanted to reproduce as much of the experience as possible within a very short timeframe.

At the University of Sheffield in March 2020, there was a window of approximately one week between face to face teaching being suspended and a full lockdown of the campus. MEE were able to use this time to prepare to deliver remote practicals while working from home, by recording videos and data. The teaching technicians were fully engaged in this process and their expertise allowed an enormous amount of recording to be carried out. Staff then had about six weeks to then edit videos, prepare online quizzes and experimental data, and adapt their assessments for each activity. This also entailed discussing and negotiating with the module leaders the experience that their students were going to have in lieu of the timetabled practical sessions. The activities were ready for delivery after the Easter break and were delivered to students between the end of April and early June 2020.

What follows is a series of short case studies covering a wide variety of engineering subjects and approaches taken to mitigate the issues around the sudden curtailing of laboratory access. We hope that these will inspire others to be able to continue to provide students with a reasonable practical experience when university laboratories are unavailable. We have chosen to present a small subset of all our case studies (CSs) in this work, which collectively demonstrate the flexibility and diversity of delivery methods that can be implemented across engineering fields even on short timescales.

However, many more teaching activities had to be adapted for online delivery, hence an even larger number of other CSs is presented in the Appendix.

Table 1 summarises all of the CSs presented in this paper, with those in the Appendix marked with an asterix (*) and located towards the bottom of the table. It indicates which delivery methods were utilized in teaching each practical subject.

Table 1: The case studies in this paper and its appendix.

	Video of the experiment	**Video instruction**	**Experiment performed at home**	**Data analysis**	**Simulation**	**Quiz**	**Student - staff interaction**
1 Magnetic materials	**X**	**X**		**X**			
2 Protein separation and validation	**X**	**X**		**X**		**X**	
3 Pilot plant experiments					**X**		**X**
4 Flow in pipes and valves		**X**	**X**	**X**		**X**	**X**
5 Heat exchangers		**X**		**X**		**X**	
6 Design, manufacture and test of LEDs	**X**						**X**
7 Circuit design					**X**	**X**	
8 Control and instrumentation	**X**			**X**	**X**	**X**	
9 Robotics					**X**		**X**
***10 Cement making**	**X**			**X**			
***11 SEM instruction**		**X**					

	Video of the experiment	Video instruction	Experiment performed at home	Data analysis	Simulation	Quiz	Student - staff interaction
*12 Biopharmaceutical Engineering	X						
*13 Bioreactor Engineering	X			X		X	
*14 Fabricating a super-hydrophobic surface	X			X		X	
*15 Frictional losses in pipes				X		X	X
*16 Mohr Circles for a hole-in plate				X			X
*17 Jet engines and the Brayton cycle	X			X		X	
*18 Optics	X	X		X		X	
*19 Electrical machines and drives	X	X		X		X	
*20 Extra-curricular electronics		X	X		X	X	X

A series of case studies on remote practicals from MEE at the University of Sheffield

1 Magnetic materials

An experiment in magnetic materials illustrates measuring the response of two different magnetic materials (soft and hard) under a changing external magnetic field. A video was captured of the experimental setup required to collect data across a range of field strengths generated by an applied voltage.

A teaching technician created a recorded walkthrough of the data analysis methods using a spreadsheet. The students were required to draw a hysteresis loop from the supplied data collected, by integrating and normalising the values of magnetisation from the electrical signal. This was a section of the practical where the students typically struggled, justifying additional effort in the presentation of this material.

2 Protein separation and validation

To explore how the function of cells and tissues can be investigated as well as practice techniques used in disease testing and diagnosis, 2nd and 3rd year bioengineering students carry out protein separation using gel electrophoresis and validate the presence of a particular protein using antibodies. A video of gel electrophoresis was produced with the same level of detail as provided in the lab script, so that students could still calculate the concentration of protein solutions obtained and provide answers to an online test. A series of captioned figures showing the expected data from the experiment allowed students to analyse and interpret the data.

To demonstrate how antibodies can be used to validate the presence of a particular protein, several online resources were used and a game that is usually played during the lab session was recreated online to help students apply their knowledge and determine how antibodies are selected when designing an experiment (Figure 2). Additionally, students were asked to compile a 750 word report discussing the use and limitations of the techniques in research and medicine, providing relevant examples, including an example of how antibodies are being used in the fight against COVID-19.

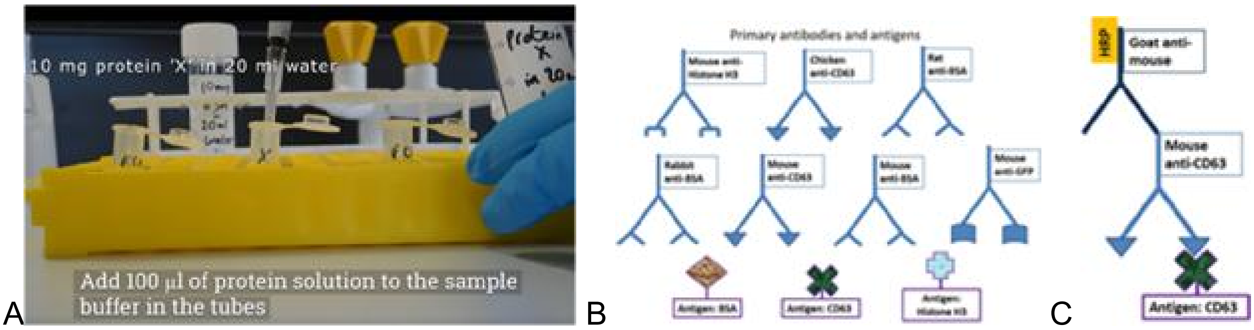


Figure 2: Video stills showing (A) the preparation of the protein samples (B) images of different antibodies used in the antibody game. (C) Answer to an online test question.

3 Pilot plant experiments

Experiments which usually utilise the Diamond Pilot Plant facilities, shown in Figure 3, allow for complex and open ended investigations which are challenging to develop into online activities[13]. The industrial scale chemical processing rigs permit the exploration of several process parameters. Students use the rigs to conduct experimental investigations and collect data for further statistical analysis. One of the main LOs in these activities is planning a Design of Experiment (DoE), which students are required to carry out using statistical approaches before arriving at the lab. Students were to be interviewed in the lab by a GTA to check their DoE, before executing their plan and collecting data during the session.

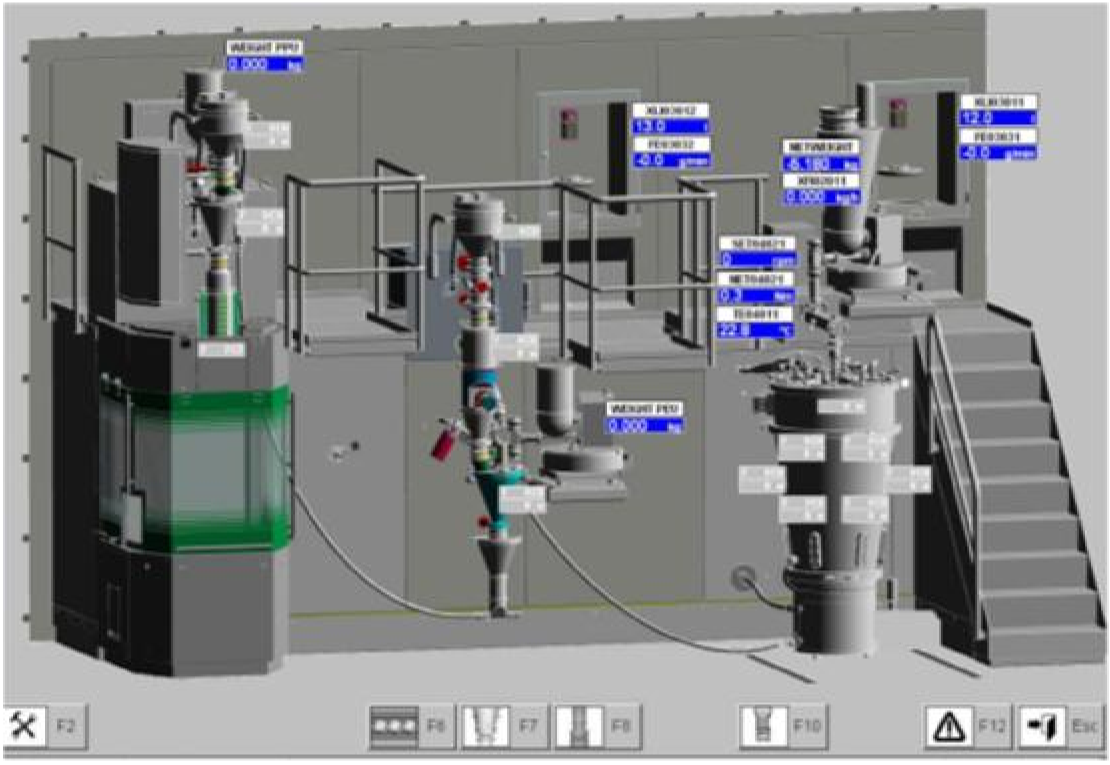


Figure 3: ConsiGma25 powder to tablet line, showing the complex unit operations with wide range of process parameters to be controlled to produce pharmaceutical tablets

Two strategies were used to provide remote practicals. Initially, students were asked to carry out their pre lab preparation and DoE as normal. However, this was submitted as online VLE assignments to substitute for the in-lab assessment. The execution of the DoE was then conducted by proxy, where GTAs (who were initially still allowed in the plant despite the suspension of face-to-face teaching) conducted the experiment and collected data for students.

The second approach was implemented after the complete campus lockdown, removing GTA access to the laboratory. Students were still required to submit their DoE as an online assignment, but data was extracted from an existing database.

An important LO of these experiments was the development of transferable skills, such as effective communication and team working. These were still achieved as students were required to do all planning and post lab reports in groups, and then complete a peer assessment form. The engagement and interaction with students and the progress of the work were monitored using weekly sessions via the VLE, where the whole teaching team was available to answer questions from students.

4 Flow in pipes and valves

Two planned practical sessions usually study laminar/turbulent flow and flow controlled by taps. The assessment of the former focused on experimental record keeping, while that of the second involved submission of a short report. These two practicals were combined and adjusted to be performed by students in their own homes. Generally, access to equipment can be variable, however, most students have access to water from a tap and rudimentary instrumentation, such as weighing scales or measuring containers. While this equipment would be less accurate than laboratory instruments and would vary from student to student, the LOs did not depend on these factors. A new assignment brief and explanatory video (including showing a staff member's kitchen with tips and suggestions on how to complete the lab) was created. Teaching material that formed the original pre-lab activity, including videos and documents of the equipment in the laboratory, was retained for the student's reference. The marking criteria remained virtually unchanged.

In addition to providing detailed guidance to allow students to work remotely, two aspects were incorporated to facilitate this mode of delivery. Firstly, students were informed that they would need to think creatively in order to engage with this activity. As this was not an explicit LO, it did not form part of the summative assessment, but as engineers need to employ creativity regularly, this was an opportunity to practice that skill. Secondly, although the activity is intrinsically safe (running water from a tap), it is important that we exercise a duty of care while instilling the need to assess risk in changed circumstances. Students therefore completed a risk assessment before undertaking any work. All taught students in the Faculty of Engineering are trained in completing risk assessment as one of their first timetabled activities, called "the Danger lab"[14]. Any work received without a completed risk assessment would receive zero marks, which is usually a sufficient incentive for compliance.

5 Heat exchangers

The original aim of this first year mechanical engineering experiment was to apply the first law of thermodynamics to a practical application over a range of operating conditions. Within their studies students will often only investigate thermodynamics around a single operating point whereas in an industrial setting equipment will have an operational range. Students were required to vary two parameters (hot and cold flow rates) and capture at least 15 data points. Within the lab sessions there was often insufficient time to analyse all the data in detail, and only a few extreme cases would be investigated. When the experiment could not take place in-lab, students were instead provided with a set of example data, allowing more data analysis than would have been possible after a practical class.

Data processing was performed using a spreadsheet. Analysis using spreadsheets in-lab has been attempted previously but abandoned due to the range of student skills. Generally more confident students take over the computer whilst others look on, and the class becomes a spreadsheet tutorial rather than a thermodynamics practical. A significant portion of the students have little or no spreadsheet experience and find their use alienating. With this in mind, videos were created showing partial analysis of the data, including calculations and the creation of scatter graphs. Emphasis was placed on the professional production of charts. The final online exercise consisted of 5 parts:

- 14 minute recorded presentation introducing the equipment and background theory;
- 11 minute video detailing data processing;
- 10 minute video examining the production of scatter graphs;
- 12 minute recorded presentation reviewing the resultant figures; and
- 6 question online quiz consisting of multiple choice and calculation questions.

Two attempts at the quiz were permitted to encourage the students to attempt the quiz and then correct their mistakes. It was decided to keep the assessment as close as possible to the original planned experiment. In future iterations the assessment could be adapted to test and encourage the use of spreadsheet processing. Furthermore, data visualisation with scatter charts revealed further depth to the data, permitting more advanced concepts to be observed e.g. the impact of fluid dynamics on heat transfer. These observations formed a useful primer on heat transfer which the students are introduced to later in their studies.

6 Design, manufacture and test of LEDs

MEE has a bespoke teaching Cleanroom. This 300 m^2 facility has an ISO6 particulate rating, enabling the manufacture and test of electronic, optoelectronic, micromechanical and microfluidic devices with features as small as 1μm.

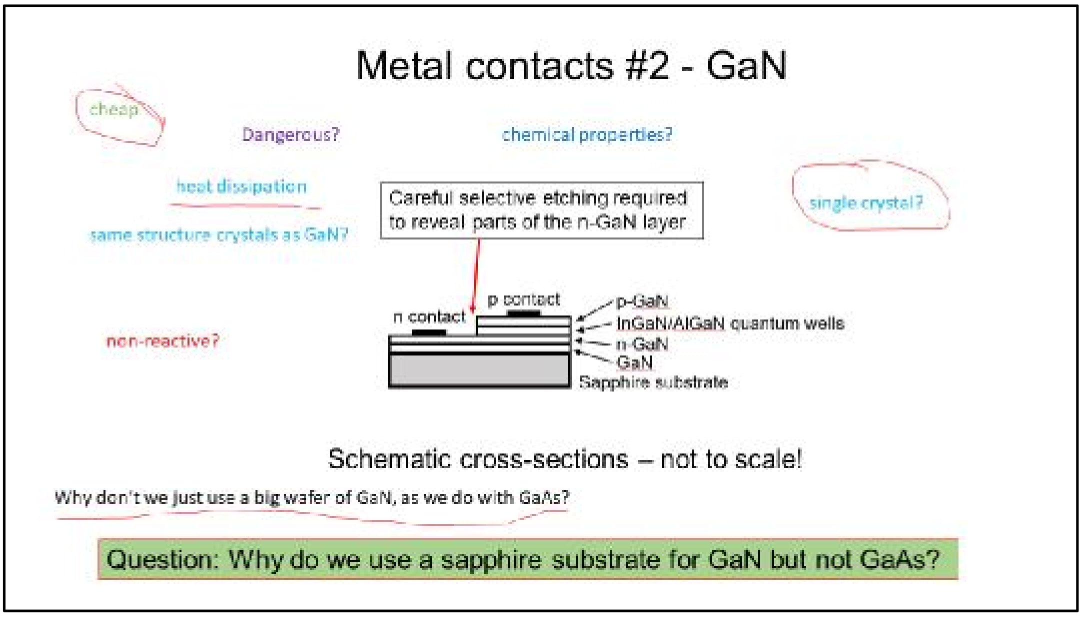
Following the move of teaching online, two two-hour online lab sessions exploring light emitting diodes (LEDs) were delivered to first year Electronic and Electrical Engineering students. The first session took the students through the basic physics of a p-n junction, followed by the measurement of the electrical characteristics (current vs voltage) of blue and red LEDs. The second session investigated the optical properties of the LEDs and finished with a discussion of the methodology for creation of white light by using a blue LED with a yellow phosphor.

The experience comprised a set of slides, supplemented by short video clips that gave the students a tour of the lab and showed recordings of the collection of the electrical and optical test data. This real data (complete with its imperfections) was shared with the students and formed the basis of their post lab analysis.

The sessions were delivered *live* via the VLE by the university teacher. This real-time approach enabled many question and answer interludes to be dispersed throughout the presentations. In these question and answer sessions, the students could remain anonymous and this encouraged them to participate. They could ask and respond to questions by annotating the slides (Figure 4).

Live attendance was satisfyingly high - greater than 50% - with the rest of the cohort using on-demand recordings. Given that students were told in advance that the sessions would be recorded, and that many EEE students are international, particularly Chinese with a time difference of 7 hours, 50% attendance at a live session is impressive. Anecdotal feedback from students suggests that they found it ‘enjoyable and entertaining’ and even a ‘highlight’ of their day! The live format added some spontaneity to the event and this has been appreciated by students watching the recordings.

The Cleanroom technical staff were also in attendance. They assisted with setting and answering technical questions. It also enabled these staff to gauge the level of understanding of the students and hence to be better placed to help with marking and giving feedback on the post lab tasks.



Metal contacts #2 - GaN

cheap

Dangerous?

chemical properties?

heat dissipation

same structure crystals as GaN?

single crystal?

non-reactive?

Careful selective etching required to reveal parts of the n-GaN layer

Schematic cross-sections – not to scale!

Why don't we just use a big wafer of GaN, as we do with GaAs?

Question: Why do we use a sapphire substrate for GaN but not GaAs?

Figure 4: Screenshot of student-annotated slide from live virtual Cleanroom lab (reproduced)

7 Circuit design

An independent circuit design, construction and testing task would normally form the capstone of the practical exercises for first year electronic engineers, but as most students do not own specialist soldering and measurement equipment at home, this cannot be directly replicated remotely. Even where students may have their own equipment, the University cannot verify that their equipment is serviceable and will be used safely, so no expectations for practical work could be made.

To still teach the fundamentals of circuit design and testing, students were provided with several simulation exercises. Two freeware platforms were selected for this task, based on their wide compatibility and ease of installation: LTSpice and Tinkercad. A structured series of sessions was designed for the students to complete at their own pace, including initial guided tutorials instructing on how to use the platforms. Particular focus was placed on how to simulate realistic circuit effects that would be seen in the laboratory, such as hidden internal resistances and parasitic capacitances, rather than just illustrating ideal theoretical concepts. The final sessions required the students to perform an independent design exercise and then simulate tests of their circuit's performance against set criteria; this mirrored requirements of the originally planned practical exercise, with the omission of only manual soldering practice.

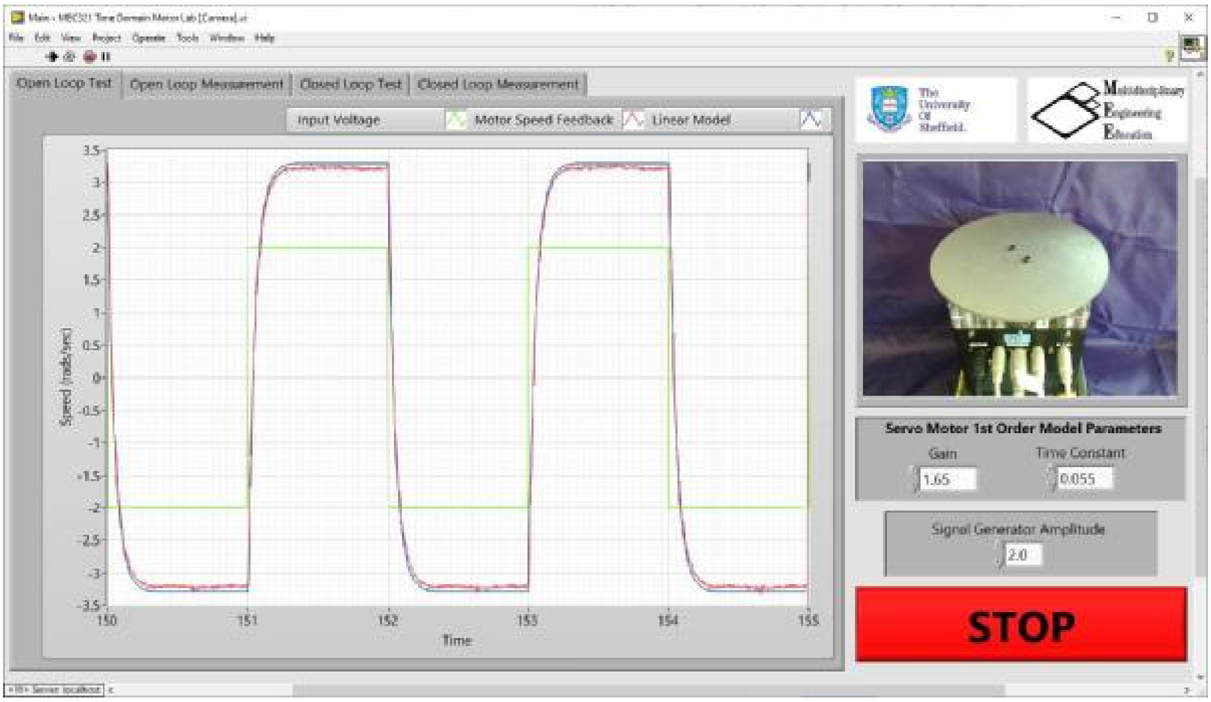
Student interaction and engagement was maintained by frequent online quizzes, which included a mixture of both automated feedback from numerical answers, and personalised feedback from staff on images and design files shared by the students. This balanced feedback structure allowed rapid turnaround of a realistic marking workload for staff, despite a cohort of 80 students. The combination of exercises and quizzes allowed learning outcomes in engineering design and experimental testing to still be met and assessed, even without physically constructing the circuits. Students should be able to progress smoothly into second year practical work, which will directly use the skills that students have acquired. However, students will need to translate their measurement techniques from virtual on-screen instruments to physical equipment, which will require careful instruction. All simulation exercises will also be integrated into pre lab work when laboratories reopen, allowing students to become familiar with circuit designs and expected results before attending in-lab sessions, to increase the efficiency and value of the in-lab practical experience.

8 Control and instrumentation

One of the challenges in providing on-line practical activities in control system analysis and design is allowing students to analyse the performance of a real system using their designs, which is easily performed in-lab. Temporary on-line replacement activities were created that closely mirrored the planned in-lab activities printed in the students' laboratory worksheets.

It was required that these activities maintain the pre laboratory exercises: analysis, design, and linear system simulation elements, but also provide the students with quality feedback to enable them to correct any misunderstandings or wrong working, without just giving them the answers. This way, the student learning journey and intellectual development progress as if staff were present, ensuring that students understand how they achieved their goal, received feedback on any mistakes made, and have a correct understanding of the topic.

Each activity employed a blend of demonstration videos (Figure 5), sample data sets taken from these demonstrations, and on-line quizzes with comprehensive feedback to ensure the students have measured the correct values, analysed the data correctly, and showed understanding of the results. A key factor to these activities was the structured sequence of the presentation of this material, which was facilitated using the VLE.



Servo Motor 1st Order Model Parameters

Gain: 1.65

Time Constant: 0.055

Signal Generator Amplitude: 2.0

Figure 5 Screengrab showing experiment and response.

The activities were split into sections, with successful completion of quizzes used to adaptively release material for the next section. Students were required to complete a pre-lab worksheet section, alongside the demonstration video, before starting the quiz for that section. Design sections had an initial quiz before the release of the remainder of the material and a final section quiz. This allowed design of controller parameters calculated by the students to be assessed before the ‘instructors’ values were revealed to them in a demonstration video.

Each quiz was automatically marked and comprehensive feedback was provided to students to help correct any mistakes. The quizzes were generally a blend of multiple choice, numerical value, multiple answer, or jumbled sentence questions. Students needed to get full marks in each quiz before they could continue, but had unlimited attempts at each quiz.

For each incorrect answer, feedback was provided to the students, signposting them to background resources in the worksheet, VLE or course lecture notes, and, if necessary, they could email staff for further advice. This allowed students to make mistakes, but they could persevere and engage to truly understand the subject.

9 Robotics

The University of Sheffield had invested £400k in state-of-the-art robotics hardware to provide undergraduate students with industry-relevant, hands-on practical robotics experiences. A brand new 12 week practical lab course had been developed around this hardware and was being delivered to second year Computer Science undergraduates for the first time, when the laboratories were closed. When an alternative approach needed to be devised, it was important to maintain continuity with the partially-delivered course but without access to the physical hardware.

The open-source robot simulator *Webots*[15] was selected as the most appropriate platform to deliver a simulation-based alternative to the practical laboratory sessions. The students would have originally, in groups, programmed their real robots to complete a series of tasks in a *final challenge* at the end of the semester in a real *'Robot Arena'*. Using Webots, a representative robot arena could be simulated, so that students could still learn how to develop the same core robot behaviours that would fulfil the original challenge, thus still achieving the original LOs.

A number of benefits were identified as a result of this simulation based approach. Firstly, a series of separate *'development arenas'* (Figure 6) could be provided to the students to allow them to develop and test individual robot behaviours in isolation, before amalgamating these into a single, multi-layer controller.

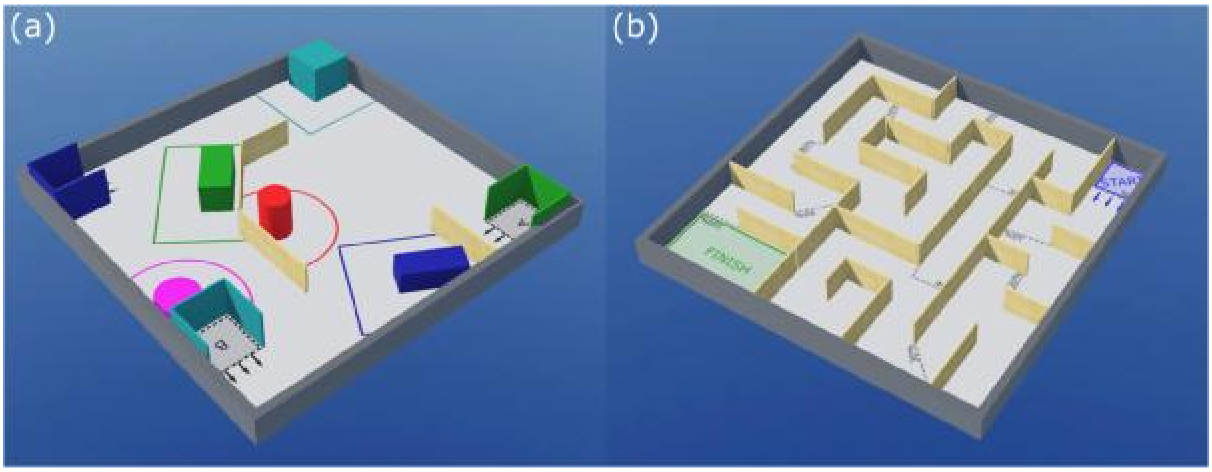


Figure 6: Robot 'Development Arenas' for (a) object search and detection and (b) maze navigation

Secondly, these arenas were distributed to students via a VLE, and they therefore had unrestricted access to develop and test whenever they wanted to, rather than being limited to scheduled lab hours. Finally, an additional element was also introduced into the assignment where students were required to develop robot hardware from scratch in the simulator. This exercised their ability to consider the physical, geometric and technical constraints such as limitations of sensors and actuators. Some student robots are shown in Figure 7.

Figure 7: *Examples of some innovative student-designed robots*

The use of a VLE was at the heart of this work. Detailed lab instructions were released to students and updated regularly via the VLE, as well as all the necessary simulation files for students to develop and run their robots in Webots. A discussion board was set up to provide a forum for students to post questions. It was monitored regularly so that support and guidance could be provided to students in a timely manner. This was found to be very effective, providing a space for students to voice questions and concerns (technical or logistic) and for facilitators to address topics and publicise responses without having to reiterate to students individually.

Whereas the original assessment would have been based on showcasing their robot's performance in the robot arena, students instead submitted videos of their robots performing the equivalent tasks in the simulator. Staging intermediate task submissions at various points throughout the lab course was an effective method of checking student progress and monitoring overall engagement. In the final challenge, students submitted their robot and multi-layer controller scripts for entry into a competition, using an arena configuration that the students do not have prior knowledge of, thus testing the robustness of their developed robot behaviours. They were ranked in a league-based competition, and a video of their robot's performance was provided to them once the competition had taken place.

Discussion

The sudden appearance and effect of the coronavirus has caused major disruption to the education sector. Generally, this is not a good thing for the student experience, but it can encourage teachers to think outside the box. It can provide the impetus to create approaches that staff have not previously had the time or opportunity to investigate. This is particularly true for practical sessions and laboratory experiments, where students engaging with equipment, working in groups and making mistakes are crucial elements embedded in programmes and providing some module LOs. As most of our laboratories are formative, there was no need to worry unduly about plagiarism and collusion. However, as exams were also moved online at the same time, summative lab assessments were performed under conditions already deemed appropriate for formal examinations, excepting longer time windows being permitted for candidates to attempt the assessment tasks.

As the numerous case studies provided in this paper show, a number of approaches can be used to mitigate the loss of the actual practical experience, such as take home experiments, remote control of equipment, technical staff carrying out experiments for the students, simulation and video replacement of the experiment. It can be seen from the variety of strategies used, that positioning remote practicals as a valuable active learning experience rather than just a recording of the experiment is key to getting students to actually engage with and understand the experiment. Simulations, remote face to face sessions, quizzes, real and simulated data, gamification, and edited videos for students to collect data from all allow high level engagement. This allowed the experiments to be more interactive than just using videos to show what was happening. To corroborate the findings of the literature survey, it is easier to provide substitute and remote laboratories where there is usually a computer between the equipment and the user. In this case, true remote experimentation is possible.

It is unlikely that this work would have been prioritised in “normal” times. As well as providing a simulacrum of a practical experience, the work put in at this time will actually improve the student experience in the future; much of the material produced will be used to enhance our pre labs to prepare students better in advance of the laboratory activities. For example, extra information and practice can be provided by videos on analysing data, which will remain available for students going forwards to support their learning, such as described in CS1.

It must be reiterated that these replacement activities will not be able to substitute for and support all the skills that quality graduate engineers need. Indeed, the UK Engineering Council in its accreditation documents[16] has a complete section on Engineering Practice where one of the requirements is the “Ability to apply relevant practical and laboratory skills”. It is clear that this cannot be conducted purely through virtual means. If it turns out that students cannot attend university campuses for a period of years, these will need to be provided for in other ways, with the associated Health and Safety aspects of working unsupervised. Without the addition of copious resources, remote practicals will generally only be able to supply some of the skills needed to function as engineers in the workplace. For example, commercial pilot training is now provided almost exclusively using simulators, but this is both low volume and very expensive.

Moving practical teaching online presented us not only with the challenge of how to provide the students with the experience and skills that each practical session offered originally, but also how to receive feedback from the students about their engagement in these activities. Previously we could easily receive verbal feedback from the students during the laboratory practicals, either directly from them or through our GTAs. Additionally, MEE developed a system for recording student satisfaction anonymously during laboratory activities where they simply press one of four facial expressions displayed on a tablet to indicate how they feel about the activity they have just completed. This has allowed us to identify the practicals that the students struggled the most with and modify them for subsequent cohorts. Away from the lab, both of those channels of receiving student feedback have been blocked.

To mitigate the lack of feedback, a simple online form was created that students are encouraged to fill out after each online activity. The form was written for fast completion so that it encourages as many student responses as possible. There are only 7 compulsory multiple-choice questions, to which students can reply on a Likert scale and 2 optional open-ended questions concerning the specifics of what they liked about the activity and what we could do to improve it. Crucially the students are asked whether they believe that the online activity was an adequate replacement of the practical activities under the current circumstances and whether they think they gained comparable skills and understanding to what they would have in a laboratory.

The information that we gather will help us not only to improve our online delivery of the laboratory teaching in the new academic year, but also rethink and redesign our activities for the future. For example, it will be possible to assess whether the LTSpice and Tinkercad approaches described in CS7 gave the students comparable skills and understanding to an in-lab experience. If true, then we could continue to provide basic circuit design teaching in this way and utilize the staff, laboratory and financial resources that would have otherwise been required to instead offer students face-to-face teaching of more advanced industrial concepts and/or more creative open-ended projects that truly benefit from interactive teaching.

Due to the strict time constraints, it was not possible to obtain ethics approval to report on student feedback we received on the strategies we implemented, so only anecdotal evidence is supplied. However, a lack of student complaints and high completion rates is a first order indication that students were engaging with the experiments and finding them useful. Initial results from student feedback surveys indicate that while they appreciated the effort and it helped their learning, they really did prefer face to face practicals

MEE were in a good position to be able to move laboratory teaching online, as a department dedicated to delivering high quality practical teaching with a student body that is used to carrying out pre lab activities online. This meant that it was possible to take a reasonably unified top level approach, combined with a myriad of ways of delivering and engaging the students, to move away from face to face laboratory experiments, while still being able to implement our high quality teaching within a very short timescale. We hope that readers of this paper will be inspired by some of the ideas presented here and will be able to better support students who cannot physically access laboratories to gain practical experiences. Some of the material and approaches developed will also be used to enhance the student experience in the future and ensure that when they are able to access the physical spaces they enter them better prepared to use that valuable and expensive time more effectively in their development as practical, employable engineers.

Conclusions

The approach of using the University of Sheffield's VLE to support student practical experience when face to face teaching was curtailed appears to have worked. MEE's aim to deliver original Learning Outcomes and to continue to support modules with embedded practical activities was conducted effectively.

Due to the existing infrastructure and MEE's previous experience, it was possible to video experiments, write quizzes, create new simulation tutorials, and provide other supporting documentation in a very short time. By empowering staff within a framework, suitable local solutions were developed by individual staff members and teams to address a wide range of requirements.

Recordings of laboratory experiments will never fully substitute in-person activities, but by thinking about the Learning Outcomes and the student experience, it is possible to create an effective learning environment for a short to medium hiatus in lab availability.

A variety of approaches to remote practicals have been presented. It is recommended that further work be undertaken to codify the totality of options for delivering online practicals, including the aspects of in lab activities that are suitable for delivering in a remote format and those that can only be delivered adequately using face to face teaching. This work would allow the development of a toolkit of tactics for educators to consider when required to either pivot completely to online learning or highly limit the amount of time each student can spend in laboratories due to social distancing measures

Acknowledgements

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Appendix

10 Cement making

To show cement making and testing a video of the experiment was designed for students to engage with the topic. This showed the materials and procedure for making cement mortars with different water, cement and sand ratios, and the testing of the cured materials using splitting tensile testing technique. This was more than sufficient to allow students both to answer a post lab quiz (based on statistical analysis of brittle materials) and to submit a histogram of supplied data from previous tests. These are the same activities that students would have been asked to do after the conventional face to face session.

11 SEM instruction

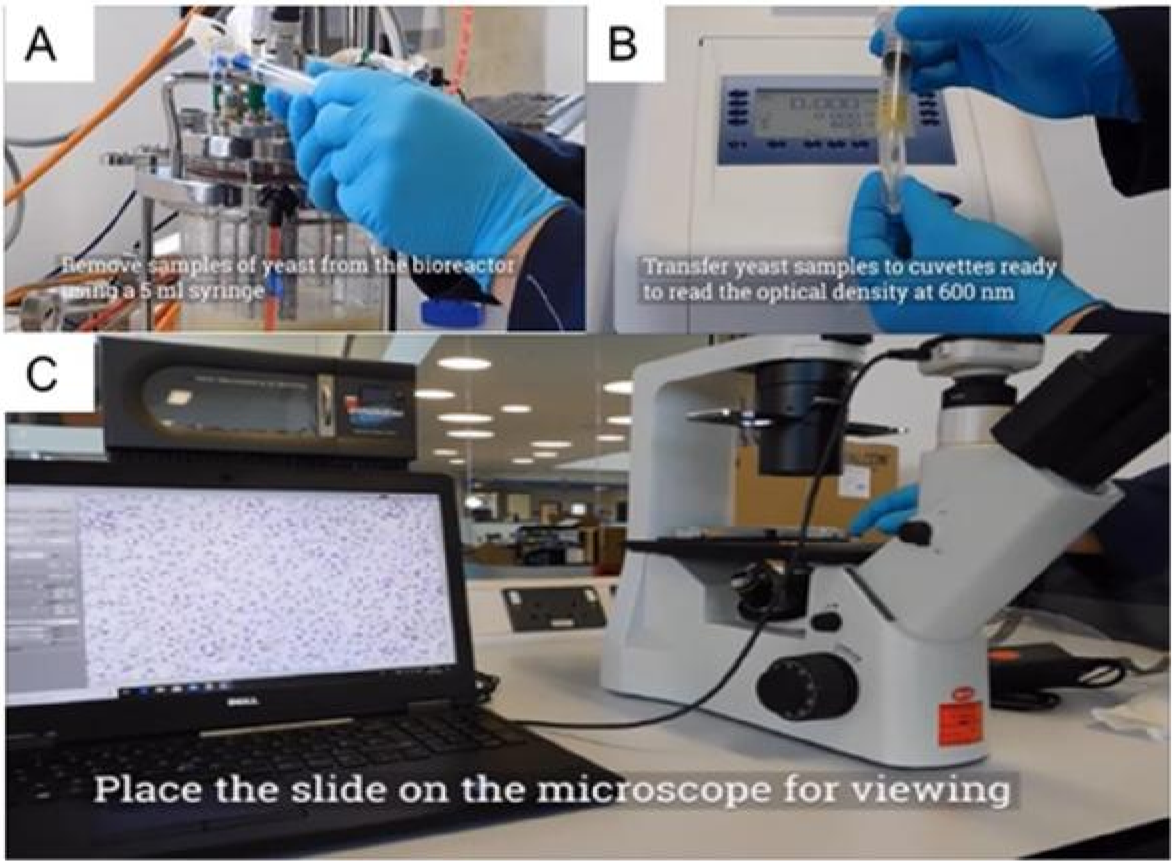
To help the students to understand the process of operating a Scanning Electron Microscope (SEM), we developed a video which explains how to load a sample correctly, take topographic images of a porous material and perform an energy dispersive X-ray (EDX) analysis on a steel alloy. This video will be a very useful tool for future training of undergraduate and project students and will be incorporated into the pre lab for the SEM sessions.

12 Biopharmaceutical Engineering

Biopharmaceutical Engineering practical laboratories were moved online by providing a video recording of all experiments the students would be expected to do, demonstrating all aspects laid out in the experimental protocols. The video was edited with comments, captions and voiceover added for clarity. Further editing kept the video concise and compact so that the students would find it interesting while helping their understanding ready to answer post lab questions. Questions were set and sent to students matching the expected outcomes from their watching the video. Some parts of the experiment could not be filmed in the available time, but relevant data was simulated or acquired to supplement the videos. Examples of some of the remote practicals are the “Antibiotic Production” (Figure A.1) and “Fermentation kinetics” (Figure A.2) experiments.

The online teaching saved a lot of time by demonstrating the experiment just once for a large cohort of students. In future, live streaming the experiments with some online monitoring tools could be added, which will allow the students to manage experiments online, similar to a hands-on experience.

Figure A1: Set up of the antibiotic production experiment.



Remove samples of yeast from the bioreactor using a 5 ml syringe

Transfer yeast samples to cuvettes ready to read the optical density at 600 nm

Place the slide on the microscope for viewing

Figure A.2, (A) is the fermentation kinetics experimental setup, (B) to Using the spectrophotometer. (C) The stained yeast cells from the bioreactor.

13 Bioreactor Engineering

Bioreactor Engineering forms a part of a third year Chemical and Biological Engineering module entitled “Reaction Engineering 2”. The LOs of the “bioreactor engineering” laboratory session were centred around students gaining a practical understanding of how bacteria grow in controlled conditions using an industrial scale bioreactor, as well as on the analysis of data to identify correlations between different parameters relating to the bacteria within the bioreactor. The experiment consists of an interactive demonstration of the bioreactor to small groups of students. During these sessions students would be asked to identify relevant measured and controlled signals, before collecting a sample of the bacteria culture from the bioreactor and measuring the optical density (OD) using spectrophotometry. Following this, the students would be presented with a data set from a previous bioreactor fermentation run and expected to identify correlations between various measured parameters and calculate values, such as specific growth rate.

Online, a video was created explaining the functions of the bioreactor, showing key parts of the equipment and explaining how measurements of the culture inside are made. Screen captures of the human-machine interface were included in this video and students were instructed to pause the video at certain points to note down key values from the screen captures for use in an online test (Figure A.3). The video included a member of technical staff demonstrating manual sampling and OD measurement of the culture, which the students were again instructed to record.

A data analysis instructional document was prepared for the students, explaining what data analysis they should perform on the provided sample data set. To improve students proficiency in working with large data sets, students were provided with a video on how to “clean” data and instructed to reduce the number of data points. Student performance was assessed using a test on Blackboard that required students to make calculations using the “clean” processed data. Feedback was given automatically to correct any mistakes.

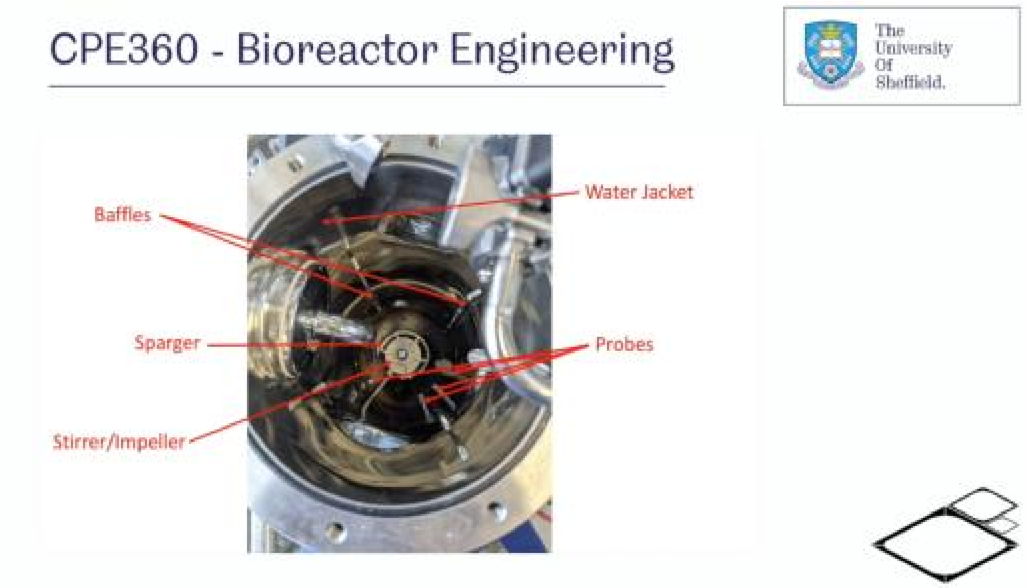
Through the creation of the online content to support this laboratory session, all LOs were able to be met. The online delivery of material also allowed all students to receive the demonstration, albeit without the hands-on aspects, simultaneously, overcoming the issue of limited space within the laboratory itself. The lack of requests for clarification regarding both the video demonstration and the analysis exercise, coupled with the high average grades in the VLE quiz, indicates the students gained a good understanding of the material covered online, as they would in the laboratory session.

CPE360 - Bioreactor Engineering

The University Of Sheffield.

CPE360 - Bioreactor Engineering

The University Of Sheffield.



CPE360 - Bioreactor Engineering

The University Of Sheffield.

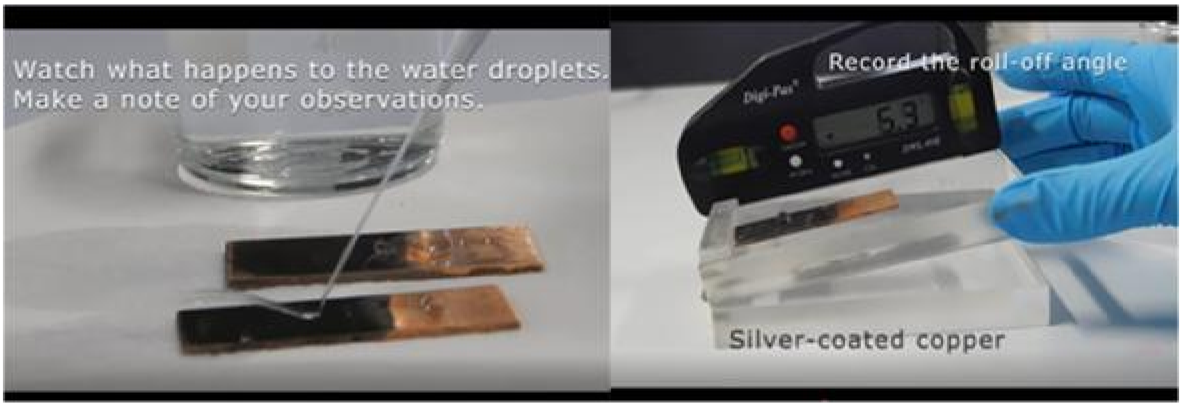
Figure A.3: Teaching material provided to students

14 Fabricating a superhydrophobic surface

As part of Bioengineering and Materials Science students' regular practical education, students investigate how biomaterials can be modified for various biomedical applications. Normally, they fabricate a superhydrophobic surface, investigate the water contact angles of several different materials using two different methods, and then evaluate the methods and the results.

Without access to the laboratories and to meet the LOs of this lab based learning activity, a video was created of the experimental procedure that demonstrates the fabrication of a superhydrophobic surface, as well as demonstrating the two methods used to measure the water contact angles on seven different materials (Figure A.4). The video had instructions for students to make observations and record the measurements from each method, so that students could still evaluate their results as they would have done had they been able to attend a practical lab session in person. Students were required to submit their observations, table of recorded measurements and summary of the results, including a comparison of the accuracy of the two techniques used to measure water contact angles and a rank order of materials in terms of hydrophilicity/hydrophobicity through the VLE for assessment, and feedback was provided to each student in the cohort.

Students completed all parts of this online learning activity and evaluated the results successfully. Valid statements on the accuracy of the techniques used in the experiment were made, including the impact of experimental errors on the recorded measurements. The answers provided by students were more comprehensive than would normally be given during a face to face lab session, possibly due to less time restraints. Therefore, this online activity could be used in future as an alternative to attending a session.


Watch what happens to the water droplets.
Make a note of your observations.

Record the roll-off angle

Silver-coated copper

A B

Figure A.4. Screengrabs showing the (A) the properties of a fabricated superhydrophobic surface and (B) investigating hydrophilicity and hydrophobicity.

15 Frictional losses in pipes

Due to the empirical nature of the fluid mechanics involved, an experiment investigating frictional losses in pipes traditionally involves the collection and processing of many data sets by students to find coefficients. In order to meet the activity LOs, raw sample data previously collected by staff using the same equipment was provided to the students for processing. In addition, an extensive pre lab activity, showing the layout, function, operation and instrumentation of the equipment used as well as a detailed lab sheet explaining the aim and procedure to collect and process the data was included.

A video and step by step instructions explaining the origin of the data, including the fact that it may contain experimental errors, was provided on the VLE to ensure students fully understood how the activity had been augmented from the original description and the alternative tasks they should perform. In addition, a live video conferencing session, using Blackboard Collaborate, was set up to allow students to interact with staff and discuss questions they had about the lab. While the material allowed students to work asynchronously, the live sessions provided an opportunity to encourage a completion of the tasks as a group, and partially recreate the sense of community often found during face to face practicals.

16 Mohr Circles for a hole-in plate

The main LO of this experiment, consisting of the tensile test of a plate with a round discontinuity in the centre, is data analysis (drawing Mohr's Circles). The experimental investigation usually takes only up to 25% of the overall session time. It was thus decided to remove the experimental section and focus entirely on the data analysis for the online replacement activity.

A dataset available from a previous year was uploaded to the VLE, together with additional visual support including a sketch of the geometrical parameters (intended to give some context to the provided data (see Figure A.5 top left)) as well as the same plot of strain over time that students would measure in the lab (see Figure A.5 top right). Students were referred to the instructions provided in their lab sheet to complete the data analysis (see a student drawing in Figure A.5 bottom left). In addition, the expected numerical and graphical solutions for the provided dataset were made available to the students (see Figure A.5 bottom right), but with a caveat. Taking advantage of the adaptive release offered by the VLE, solutions were only available to students that completed the online pre lab activity, as a measure intended to ensure a sufficient level of preparation before engaging with the practical. Finally, to support students in the completion of the data analysis, one to one discussion with staff was available via email.

The outcomes of the summative assessment suggest that the measures put in place were effective, with most students performing well. Two main considerations are required when deciding whether this type of approach is viable. Firstly, replacing the experimental component with a dataset was only possible because the session primarily focused on data analysis. Secondly, engagement may become a problem when this approach is applied to non-assessed sessions (with typically lower engagement) as it lacks live interaction with students. Measuring student engagement remotely is challenging. One option could be looking at the enquiries made by students for any specific session. However for a non-assessed session, no student queries were received as opposed to the daily ones for the assessed session. Another method could involve implementing an easy quiz that would replace the requirement for students to be physically present in the laboratory to effectively pass this activity.

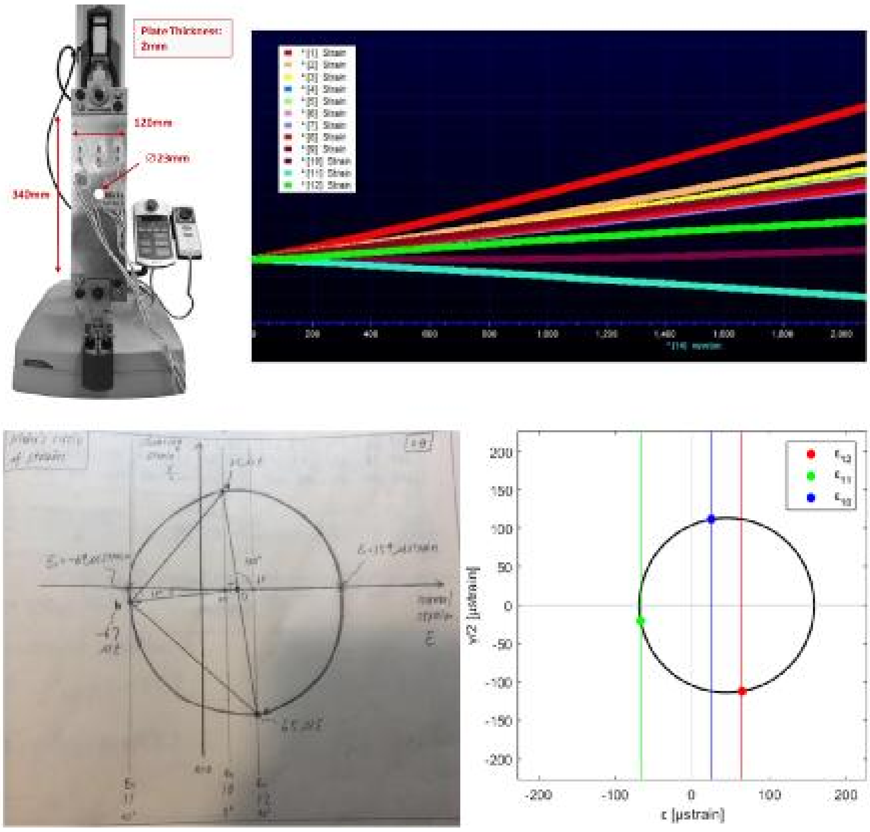


Figure A.5 Example of information provided to students and some student work (used with permission)

17 Jet engines and the Brayton cycle

One of the key parts of engineering is the application of the theoretical to the physical. Managing this process is key to the manufacture of complex systems, such as a jet engine. To this end, we have a running jet engine within MEE, that is used principally by first and second year aerospace engineers. This sits in a sound-proofed engine test cell, within a dedicated propulsion lab. As such, it serves two purposes: in one it is a complex machine, but in the other it is an example of the laws of thermodynamics; it is a link between the real and the ideal.

In their first year thermodynamics module, the last subject covered by aerospace engineering students is the Brayton cycle, allowing them to look at the performance of a jet engine in ideal and real situations, and thus work out the efficiency of the machine. This is taught in lectures, where it is assessed by an online test. However, to complete the experience and show how real systems work, the running engine provides an example, the understanding of which better prepares the students to undertake the online test, as they have seen, smelled and heard the engine operate, before taking data to process from the real engine.

A video was prepared, starting with a cut-away model of the engine, moving through the test cell and explaining the test engine's instrumentation, before showing students the data acquisition system and discussing the test protocol (Figure A.6). This allowed the students to see how the data was collected, but also to understand how the data was measured, and in which parts of the engine the necessary sensors were placed. This is highly representative of the experience of practicing engineers, who would often be remote from the testing of things they had designed. Hence, the move online provides us with a further learning outcome in practical engineering.

Figure A.6: Video still showing operating of the engine

Test data obtained in the video that they watch is provided for analysis, and the method of calculation is explained in a laboratory script. However, the data from the engine is left in the original format so that values need to be converted to consistent units, and some factors need to be calculated using equations that the students have previously employed. The general principle is that the data should be as pure as possible, so that the students have to work out the steps necessary to perform the calculations themselves. Following this, a quiz is provided as a self-test and so they could obtain feedback if they are struggling. Successful completion of this quiz opens up the online assessment test, such that they have every opportunity to complete the assessment even in the absence of the intended hands-on experience.

18 Optics

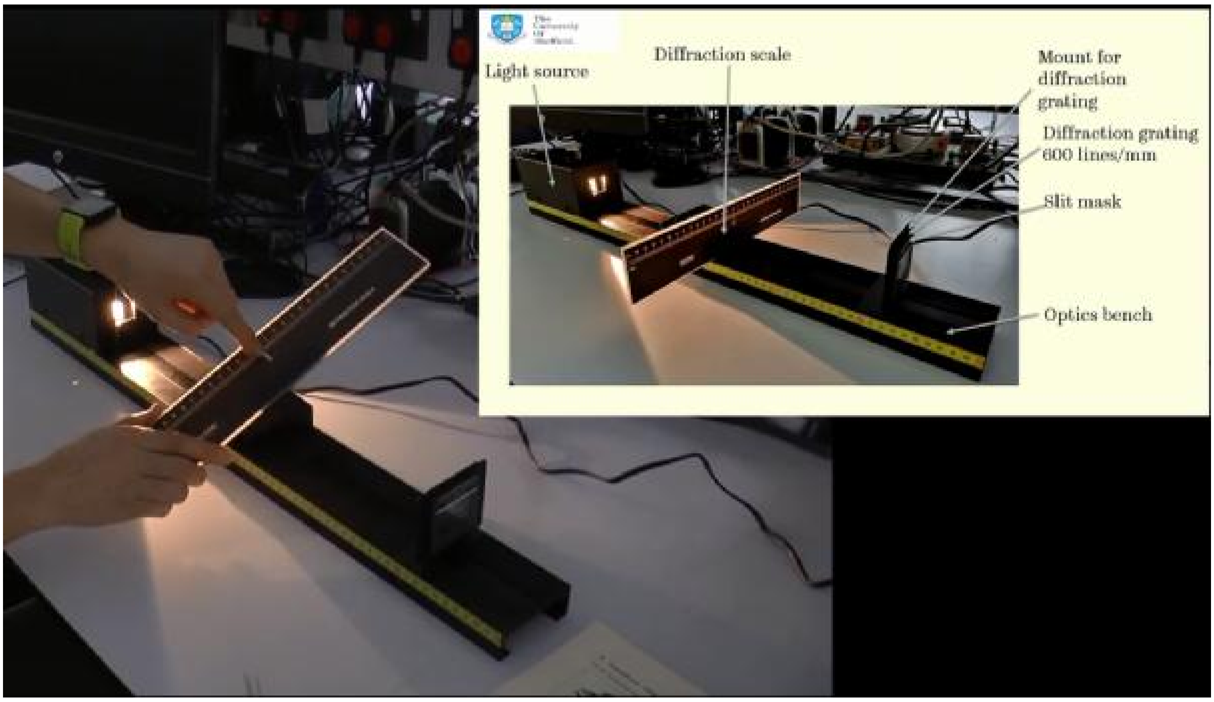
The Science and Engineering Foundation Year (FY) programme at the University of Sheffield provides a supportive learning environment to improve students' understanding and skills in preparation for degree-level study. The first FY experiment impacted by suspension of face to face teaching was optics. Normally, refraction and diffraction are investigated in two experiments using an optics bench:

i) Calculate the refractive index and critical value for an unknown material

ii) Investigate the behaviour of light through a diffraction grating and determine the wavelength of different parts of the white light spectrum

In the refraction experiment, a video replaced the experimental setup and introduction to the optics bench (Figure A.7). Students were tasked to construct a data table suitable for refraction and reflection measurements and collect data from high resolution photographs, ensuring their data maintained an appropriate level of precision. Students graphed their data and used Snell's law to calculate the refractive index from the gradient.

In the original diffraction experiment, students would sight along a diffraction scale to determine the position of different colour maxima in the spectrum of white light. This posed a challenge to provide an online version where students could collect their own data. As an alternative, video teaching was used to illustrate the equipment setup and procedure. Students used a provided dataset to calculate the wavelength of red and blue light and gain an appreciation of how to deal with measurement uncertainties.



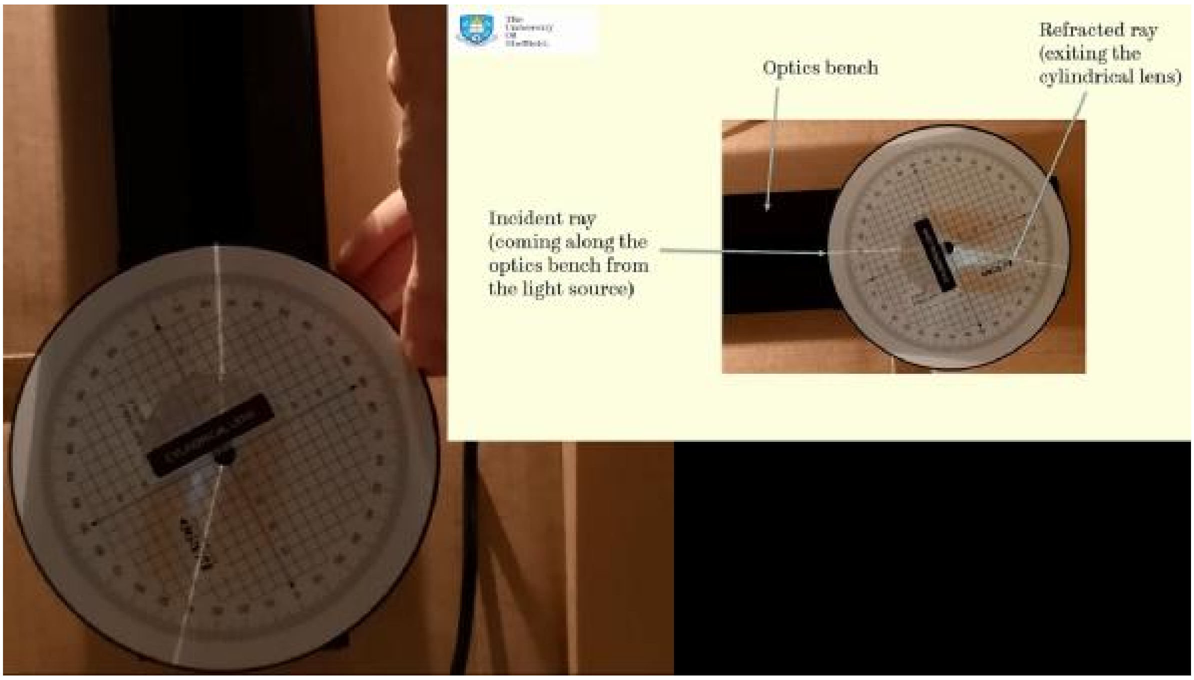


Figure A.7: Screenshots of online optics lab materials

The post lab activity aimed to foster collaboration between students to regain some of the community lost by lack of physical presence in the lab. Students were encouraged to work together to devise methods for answering the post lab questions, however, each individual was tasked with solving their problem with a unique set of operating conditions using the VLE ‘calculated formula’ question capability . Questions focused on calculations relating to scientific and engineering applications of refraction and diffraction, including fibre optics, star spectra and the eye.

Moving these experiments online gave the opportunity to assess our student’s understanding in a more robust manner as it removed time constraints and logistical issues of getting students into and out of the laboratories. Initial impressions of engagement indicate that it was almost identical to previous face to face sessions.

19 Electrical machines and drives

Moving online at a fast pace, faced us with the challenge of transforming a series of experiments pertaining to the field of electrical machines and drives, involving relatively large industrial-grade equipment, into virtual online lab activities. The series of experiments demonstrate the use of different types of electrical machines as controllable electromechanical energy conversion devices and investigate some of their fundamental operating characteristics. During the tests, several measured quantities are recorded and are used to derive other key machine parameters either directly or by using the corresponding equivalent circuit model of the machine type under investigation.

Normally, students would perform a series of tests through a LabVIEW program that controls the machine set via their associated drives. The experimental tests were filmed in the lab by following the step-by-step instructions from the existing lab script. The recorded footage has been edited into full video demonstrations of each experiment, providing students with insight on how the required measurements are obtained, by simultaneously viewing the control interface and the test rig (Figure A.8). Animations, captions and annotations have been incorporated in the videos providing students with guided instructions and highlighting key points. Datasets with the required measurement values for each experiment were provided to students for subsequent analysis and interpretation. Students were required to follow the lab script while watching the video content and perform the required calculations/plots for each experiment.

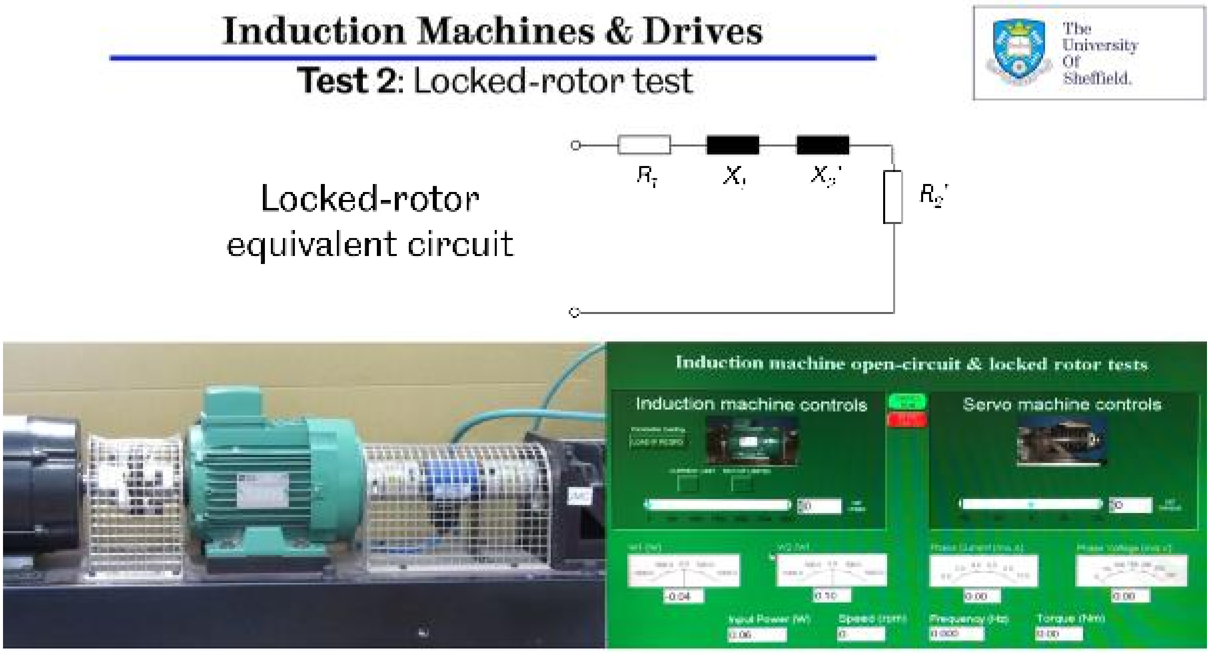


Figure A.8: Screengrab from the video demonstration of an experimental test

To fully engage students, reinforce their overall understanding of the experiments and emulate the interaction of students with GTAs that would normally take place in the lab, a self-assessed online lab quiz was developed, adding to the existing pre- and post-lab quizzes. This quiz was intended to enable students to validate their calculations as well as enhance their knowledge on the topic. This quiz was unassessed, and students had unlimited attempts to complete it. The questions contained in the quiz were organised thematically. The correct answers were never revealed upon submission. Instead, automated feedback was incorporated for incorrect answers, guiding students toward finding the correct answer, enabling them to learn from their mistakes. The feedback took various forms, such as signposting students to a relevant resource (e.g. lab script, theory) and/or targeting common student errors (e.g. steps omitted, approach). Students requiring additional guidance and support were encouraged to contact staff. However, this was a rare occurrence.

The attempt statistics of the self-assessed quiz showed a high level of student engagement with the material. The post-lab assessment results indicated that students who completed the online lab activities performed comparably well in assessment to those who completed the activities in the lab. This is encouraging and indicates the benefits of incorporating a self-assessed quiz to emulate interaction with staff alongside video demonstrations. Future sessions, both remote and in-lab, can use this blended approach to enhance the students' learning experience and engagement.

20 Extra-curricular electronics

Students from across all engineering disciplines require basic skills in practical electronics, and these skills are generally no longer provided by secondary schools. In particular, students are not proficient at building small prototype circuits or confident in exploring electronics concepts by practical investigation, despite enthusiasm to do so. Providing optional extracurricular sessions in a supportive environment, with trained staff to guide students through fun training activities, can provide a valuable introduction to practical electronics.

A regular series of optional drop-in practical electronics workshops in the laboratory has been running in the Wednesday afternoon timeslots traditionally reserved for extra-curricular activities at UK universities. These sessions have proved popular, with students from 6 different departments regularly engaging. Bespoke teaching material has been created for these sessions, focussing on practical construction and applications of electronic circuits rather than theoretical or mathematical approaches. Students have attended to develop their practical skills or construct independent projects. However, with the suspension of face-to-face teaching, the regular in-lab sessions had to be cancelled.

Ensuring extra-curricular activities continue during remote teaching helps maintain a sense of community between students, and ensures that interesting and engaging parts of the courses are not neglected. The teaching material has been moved to a publicly accessible website[1], which includes five separate sections: 1) basic electronics theory and brief explanations of basic tools and equipment, including Health and Safety, 2) description of essential practical skills, such as soldering, 3) examples of circuits, which students can build, test and modify, 4) tutorials on using an Arduino microcontroller system allowing students to learn to build and program full systems, and 5) examples of projects for students to undertake in the future. The site includes text, photo and video content, presented in the same informal and encouraging style of the in-lab sessions.

The site actively encourages the use of practical making skills, and provides a parts list and advice for students on obtaining kit or components. However, it is also possible to use circuit simulation software, such as LTspice and Tinkercad to complete many of the exercises. Students can access the materials at any time of day and are able to work at their own pace. They can also choose which activities best suit them and they are encouraged to ask questions (via email or video chat) to further develop their interests.

The sessions were previously advertised via word of mouth during taught laboratory activities and by using physical posters, so the promotion campaign moved to social media, with support from university departments and faculties to encourage students to engage. Social media has been particularly active on Wednesday afternoons, replicating the previous buzz of activity in the laboratory at that time. In future, the online teaching material can support in-lab sessions to encourage students to practice their skills both inside and outside the laboratory at any time.

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https://sites.google.com/sheffield.ac.uk/diamond-electronics/home (Accessed 27/05/2020)