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Online interactive learning experience – Virtual Laboratory based experiments in engineering

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ABSTRACT

Practical laboratory exposure and hands-on experience on core concepts is a critical part of learning and evaluation in engineering education. With the advancement of online technologies and the flexibility offered by online education, many educational institutions are progressing towards offering completely online courses. However, this is rather difficult in engineering education, as converting practical and hands-on experience to virtual laboratory continues to be a challenge.

Authors like to present the challenges and opportunities when converting physical experiments to online. These online experiences can be either via simulated environment or via interactive video exercise or via remote laboratory platform where student can control and manipulate physical equipment and conduct experiments online. They would also like to present examples of laboratory experiments and associated assessments developed in the school of Mechanical and Electrical engineering.

Introduction and Background

Distance learning has been around for quite some time now, with the first generation dating back to the correspondence-based learning (Bates, 2005). The development of technologies has opened up many new avenues and formation of information society has emerged as one of the modern trends where e-learning can assist and enable borderless dissemination of knowledge (Panasiuk et al., 2021). With the invention of new technologies every day, the concepts of distance, time and place have changed initiating a paradigm shift in educational practices in every academic discipline. The process of globalization has already started pushing all educational institutions towards universal phenomenon - ultimate realization of online higher education through Virtual University (Salmerón-Manzano & Manzano-Agugliaro, 2018). COVID19 pandemic posed the urgent need for most of the educational institutions around the world to migrate their courses to online platforms. While still learning and adapting to the unchartered territories of online classrooms, conducting laboratories online posed a much bigger challenge. This pandemic has adversely affected many hands-on aspects when the education moved online, including practical laboratories and work integrated learning (V et al., 2021).

If we check its Latin roots, the word 'engineering' has in-built aspect of creating and as per the modern definition, this profession has a lot to do with design, building and use of machines and structures (Engineering | *Definition, History, Functions, & Facts | Britannica*, n.d.). In other words, engineering is the practical application of scientific knowledge and hence engineering education must go beyond the theoretical concepts. Being application-based education, engineering education always had two distinct aspects namely classroom-based teaching and laboratory-based teaching embedded together. One cannot imagine engineering education without a practical and hands-on laboratory component (Balamuralithara & Woods, 2009).

Due to a huge demand of online education that can offer so many benefits including flexibility, availability, cost-effectiveness and broader reach (Siddhpura & Siddhpura, 2021), the research in the field of online laboratories has also seen a huge spike. A remote laboratory prototyping case for instrumentation and control was presented along with the state and prospects of the theory by (Poliakov & Rida, 2020). As discussed by (Vergara et al., 2020) and (Vergara et al., 2022), Virtual Reality (VR) based online laboratories have great potential when it comes to engineering education. Online laboratories play an important role in increasing sustainability of engineering

courses and offer quite a few advantages as discussed in Figure 1. Although, online laboratories have a huge potential for improving engineering education and offer significant benefits, they have some limitations as well which are shown in Figure 1.
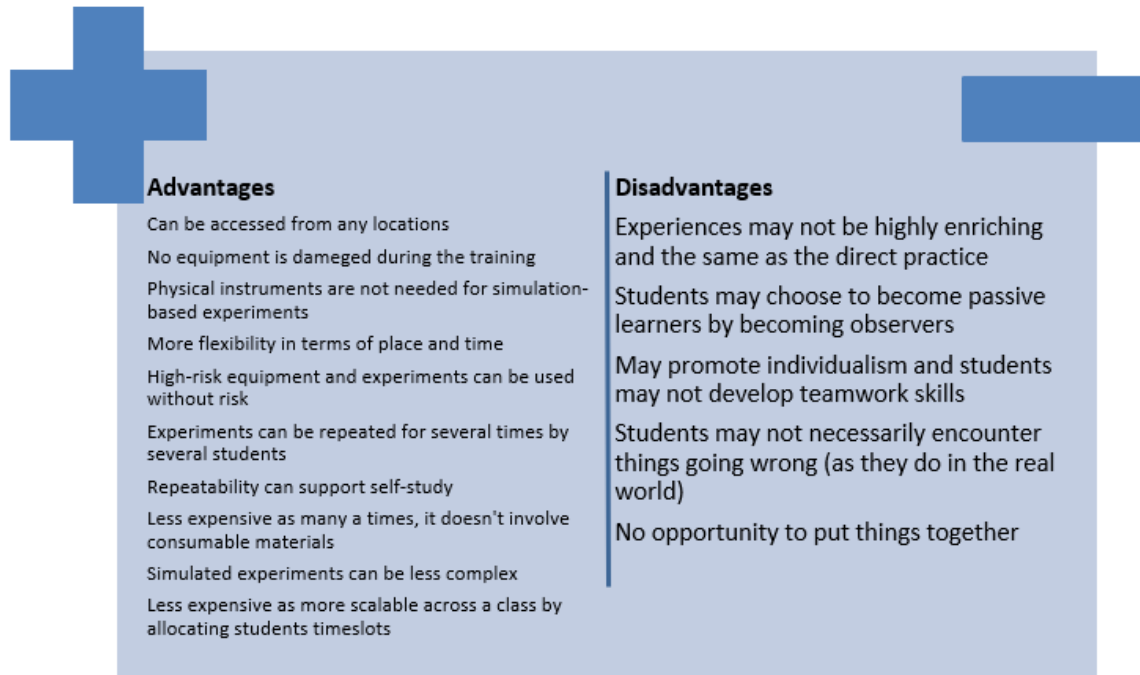
Advantages

Can be accessed from any locations

No equipment is damaged during the training

Physical instruments are not needed for simulation-based experiments

More flexibility in terms of place and time

High-risk equipment and experiments can be used without risk

Experiments can be repeated for several times by several students

Repeatability can support self-study

Less expensive as many a times, it doesn't involve consumable materials

Simulated experiments can be less complex

Less expensive as more scalable across a class by allocating students timeslots

Disadvantages

Experiences may not be highly enriching and the same as the direct practice

Students may choose to become passive learners by becoming observers

May promote individualism and students may not develop teamwork skills

Students may not necessarily encounter things going wrong (as they do in the real world)

No opportunity to put things together

Figure 1: Advantages and Disadvantages of online laboratories

Apart from above discussed limitations, one needs to consider other constraints like scalability, interoperability, extensibility, flexibility and integration when it comes to design and implementation of such laboratories in pedagogical context (Saliah-Hassane et al., 2018). We are yet to overcome some of the main challenges associated with online laboratories like reusability, interoperability, collaboration etc. that were identified by (Gravier et al., 2008) more than a decade ago. In their systematic review of more than 1600 research papers focusing on implementation of virtual laboratories in undergraduate science and engineering courses dating from 2009 to 2019, (Reeves & Crippen, 2021) reported that most of such laboratories were lacking theoretical and methodological approaches.

However, in recent decades, substantial advancements in technologies has opened the doors for successful implementation of remote and virtual laboratories. (Hernandez-de-Menendez et al., 2020) reviewed many such latest technologies that are enablers of industry 4.0 revolution and how they are being taught by various leading universities. There exists a lot of literature depicting successful implementation of remote and/or virtual laboratories. A remote laboratory was developed and successfully implemented for telecommunication students by (Monzo et al., 2021) which received positive feedback from the students as well. In their recent critical review, (Bhute et al., 2021) provided a lot insights into successfully implemented remote laboratories. In their recent article, (Fernandez-Pacheco et al., 2019) shared information about Internet of Things (IoT) remote laboratory developed using Arduino and Raspberry pie. A remotely operated testing cell for forming operations for mechanical engineering students was conceptualized and successfully implemented by (Grodotzki et al., 2018).

There are two possibilities for the types of experiments – physical and virtual and these can be accessed either locally or remotely. So, this can provide 4 different possibilities for the laboratories as shown in Table 1

Table 1 Different types of laboratories

Type: → Access: ↓	Physical	Virtual/Software-based
Local	Locally accessed physical laboratories	Locally accessed virtual/software-based laboratories
Remote	Remotely accessed physical laboratories	Remotely accessed virtual/software-based laboratories

However, in literature, online laboratories are usually classified into two groups, namely remote laboratory and virtual laboratory ((Budai & Kuczmann, 2018), (Balamuralithara & Woods, 2009)). Remote laboratory is the one where the required hardware components are connected to the network and are operated remotely. On the other hand, virtual laboratory is where the components are completely software-based and simulated remotely by the students.

In this paper, the authors have classified the online laboratories slightly differently and added a third category. Online laboratories are classified into 3 groups as explained in Figure 2.
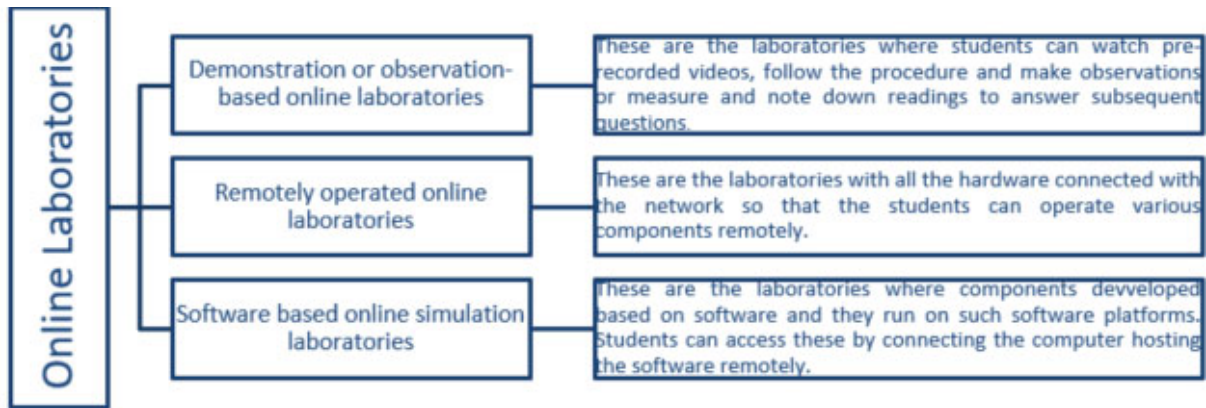
Figure 2: Classification of online laboratories

Learner engagement is an area where many academic institutes struggle. This is also evident from the Quality Indicators of Learning and Teaching (QILT) survey results (QILT, n.d.) and other recent reports (Matchett, 2022), (Shah, 2022) and (Matchett, 2022). As discussed earlier, hands on experiments are enriching experiences for the learners and introduction of remote and virtual laboratories in curriculum can help improve the student experience and learner engagement as these are accessible from anywhere and at any time. Engineering Institute of Technology has been delivering a lot of VET and Higher Education Engineering courses online even before pandemic. And hence, academics are always looking for various ways to provide similar experience as the on-campus students to the students studying online. Moreover, many of the students studying online are also working full time or part-time and in different time zones hence they need flexibility when it comes to accessing the laboratories. This paper aims to disseminate information regarding infrastructure of some remote and virtual laboratories developed by the authors to the wider community in academia. One example from each of the above category has been provided. As these laboratories are developed only recently, authors don't have student feedback or performance date yet but some pilot study results are discussed.

Approach/Methodology – Online Laboratory Examples:

Demonstration/Observation based online laboratory examples:

1. Hydraulic circuit experiment

This section covers the example of virtual laboratories which are used for demonstration, observation and possibly for some measurements. These virtual laboratory experiments were aided with the H5P package (*H5P*, n.d.), which is basically a HTML-5 plugin tool that helps create and run interactive content and interactive video within the LMS such as Moodle or other type of eLearning browser. Although, traditional video content is considered non-interactive, the H5P package helps make such content interactive. Under this category, there is a 'Hydraulic circuit' experiment which is made available to students through the unit page on Moodle learning management system (LMS). This experiment has been developed to provide the students with a thorough experience of an experimental rig with successive tasks. When students start this experimental activity on Moodle, they first go through the aim and theoretical concepts of this experiment followed by either multiple choice quiz, fill in the blanks and True/False type of questions as shown in Figure 3 to ensure that they have understood or revised the theoretical background before going through the experimental demonstration. Next, students go through a series of systematic video demonstrations to observe the 'Hydraulic circuit' rig. The first video called 'Video 1_Hydraulic circuit component identification' explains the different components of the experimental rig as shown in Figure 4 followed by a 'Drag and drop activity' created using H5P where students match the components names with component pictures by dragging and dropping the pictures under correct names as shown in Figure 5.

The next video called 'Video 2_ Hydraulic Circuit Connections Explained' (Figure 6) demonstrates how the components of the rig are connected for a given experimental operation. The next video 'Video 3_ Hydraulic Circuit Operation' (Figure 7) demonstrates how the circuit operates after switching it ON and switching some control levers on the rig. After watching these 3 videos, students are required to work on some assessment questions and numerical problems related to the hydraulic circuit explained.

In the next stage, students are taught via a series of interactive videos on creating a virtual simulation of a similar hydraulic circuit using software such as FluidSim or Automation Studio. After that, students are required to go through some software related 'Instructions and Tasks' where students are guided in downloading or accessing a particular software and then tasked to build a variety of simple and complex hydraulic circuits. Finally, students are required to submit all their assignment tasks including answers to the theory questions and built hydraulic circuits in a submission box on the Moodle page specially built for this experimental exercise.
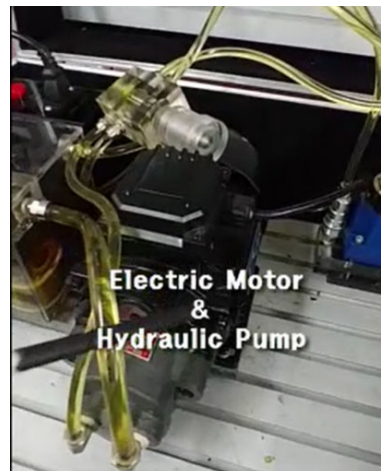
Figure 3: 'Hydraulic circuit' experimental activities   **Figure 4: Video-1**
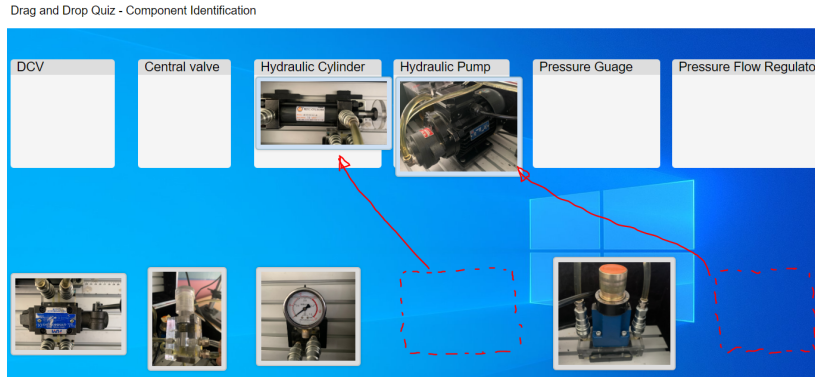

Figure 5: Drag and drop activity for component identification
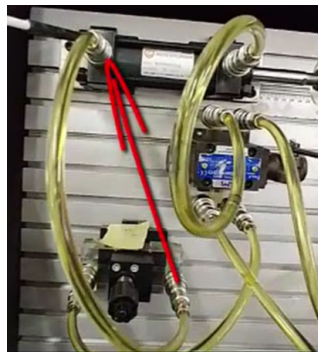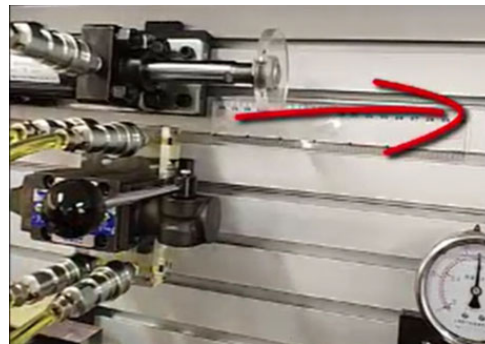

Figure 6: Video-2   **Figure 7: Video-3**

2. Pneumatic circuit experiment

For pneumatic systems, EIT has developed two experimental rigs, the first one is exactly like the 'Hydraulic circuit' presented in the previous section of this paper. The second pneumatic circuit is a small rig where the operation of pneumatic system is demonstrated to the students. As shown in Figure 8, the pneumatic components are all connected with a tiny compressor and motor along with relay switches and an Arduino Uno controller. This pneumatic rig can be used to demonstrate the operation of a fully automatic pneumatic cylinder where cylinder fully extends and stays extended for 2 seconds before retracting and it stays retracted for 2 seconds before extending again and the cycles of extension and retraction continues indefinitely along as the circuit is powered.

Figure 8: Pneumatic circuit rig

Figure 9: Pneumatic circuit modifications
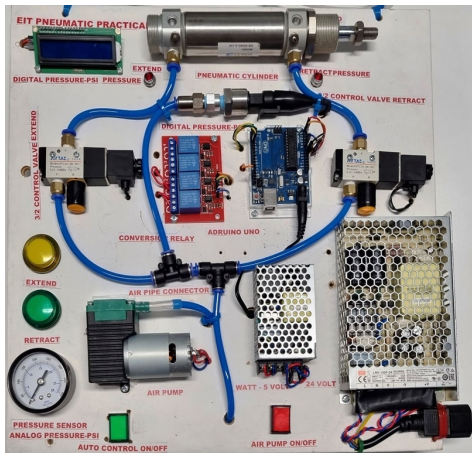
The pneumatic rig in Figure 9 can also be operated remotely via an Arduino Uno controller which is connected to a remote lab computer along with a web camera. Students can log onto the EIT remote labs to carry out a remotely operated pneumatic circuit experiment. Students can turn on the power of the rig and the pneumatic cylinder start operating continuously with a time delay of 2 seconds at the end of both extension and retraction stroke and during this student can observe how this circuit components operates in this fully automatic circuit. Students can also experiment with the Arduino program shown on the left-hand side of Figure 9 by adjusting the delay time from 2 seconds to other suitable timing. After that, students can run the experiment again to verify the new delay timing. So, if a student changed the delay time to 5 seconds, when the circuit is being operated, students can see that the cylinder pauses for 5 seconds at the end of extension as well as retraction in this fully automatic circuit. The student can write a full report about circuit's components, operation, modifications to the Arduino program and revised operation as an assessment.

Remotely operated online laboratory example:

1. 3-phase generation and distribution

This section covers the example of power generation, transmission and distribution. The main purpose of this remotely operated laboratory is to give students an understanding of the concepts of power generation and generator theory. Figure 10 shows the 3-phase power generator and distribution lab with a web camera on the top of the setup and is connected to the Graphical User Interface (GUI). GUI screen is shown in Figure 11.

The physical equipment includes a brushless DC motor driving a three-phase generator at about 3000 rpm to generate approximately 9 volts AC at 50Hz between each phase. The three generator phases are delta-connected to the primary windings of three transformers to produce about 200V at 50Hz at their secondaries. One side of each transformer secondary is connected to form the three-phase distribution system neutral.

The secondary phase to neutral voltages on each phase and the individual phase and neutral currents are measured by sensors and the respective voltages and currents are sent to the Graphical User Interface (GUI) for display to the user. The control system allows the user to individually connect either a resistive-load (40W lamp) and/or an inductive load (fan) between each phase conductor and neutral. The generated frequency is also measured and is displayed for the user.
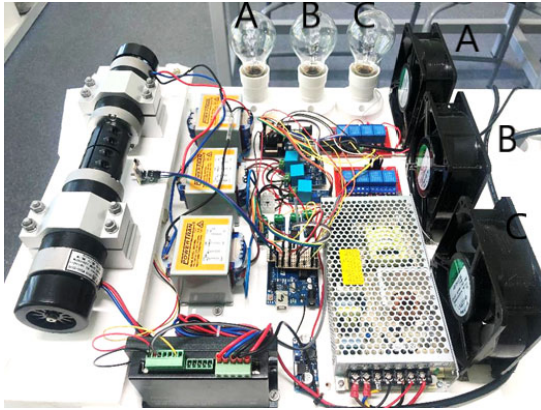
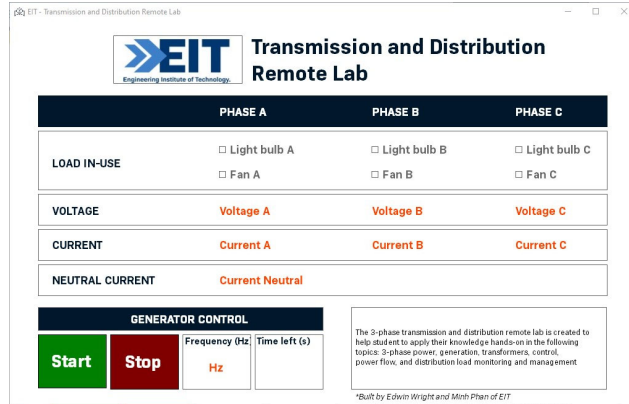**Figure 10: 3-Phase generation and distribution lab setup**

Figure 11: 3-phase generator and distribution network remote lab GUI

To operate this laboratory, the motor needs to be started by the user clicking the "Start" button on the GUI to start generating the AC voltages. A counter is used to display the time the motor will remain running. This commences at 240 seconds and the motor will stop as the timer counts down to zero. The user continues the lab operation by clicking the "Start" button at any time to reset the counter before it reaches zero. This is an essential safety feature to ensure the remote lab AC generation will always stop if the remote lab is disconnected from the user for any reason.

Students can also select between an inductive or resistive load depending on the laboratory task that they are performing. Concepts such as active and reactive power, power factor as well as characteristics and effects of different types of loads on generation can be learnt through this experiment.

The laboratory is designed for the students to understand the AC and DC power transmission networks through practical exercises. Students are expected to demonstrate their knowledge in 3-phase power, transformer, different loads and their effects (resistive & inductive), and power flow.

The laboratory is optimised to be controlled remotely, enabling all EIT's students to learn about the fundamental concepts of electricity transmission and distribution at their own time and in a safe environment.

Software based online simulation laboratory example:

1. CFD simulation of jet apparatus

This section covers the example of converting traditional applied fluid mechanics laboratory experiment into a virtual laboratory utilising Computational Fluid Dynamics (CFD) software. This exercise has been developed to provide the hands-on experience to engineering students studying via online mode. In this applied fluid mechanics experiment, investigation of the change in momentum and hence the reaction force of water jet based on the shape of the surface i.e., flat plate or curved shape is evaluated with CFD model of the jet apparatus. The results are then compared with the computed forces by applying the momentum equation. The figure below shows the traditional equipment (Figure 12-a) and the geometry generated (Figure 12-b) in the Ansys Workbench.

The energy equation can be applied between the nozzle exit point and the surface of the deflector. Two different deflectors i.e., a flat deflector (Figure 13-a) and a hemispherical deflector (Figure 13-b) based on the shape shown in the Figure 13. Water strikes on the deflector results in the change in direction of the flow, leaving the magnitude of the flow velocity unaffected.

The main purpose of the CFD simulation is to capture flow properties between the nozzle exit point and the surface of the deflector. CFD simulation is also utilised to evaluate the flow behaviour after the strike of the water on different deflectors. Step-by-step pre-analysis of the problem is

performed to reduce the complexity of the problem without compromising the accuracy of the results. The flow visualisation and hence the flow property in computational fluid dynamics depends on the quality of the mesh utilised to resolve the mesh. Mesh is defined as "a set of points distributed over a calculation field for a numerical solution of a set of partial differential equations (PDEs) (Thompson et al., 1998).
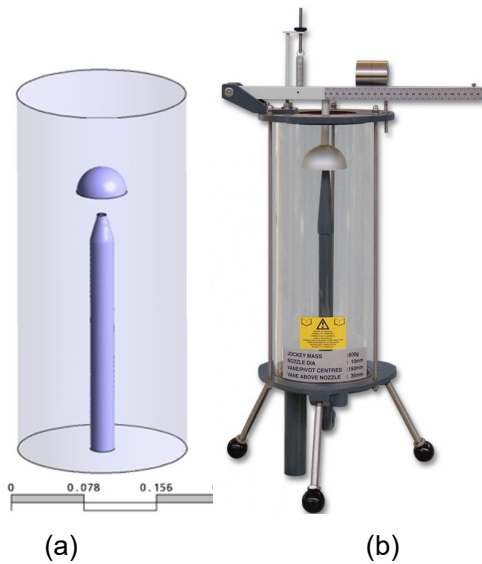

(a)   (b)

Figure 12: Jet Apparatus (a) Traditional design (b) Geometry for the CFD simulation

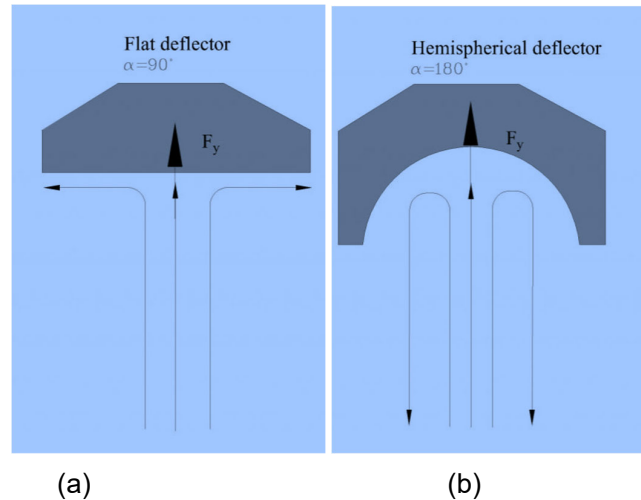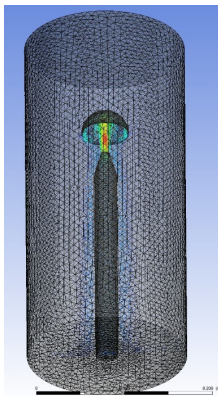(a)   (b)

Figure 13: Deflector surfaces for the jet apparatus (a) Flat shape (b) hemispherical shape

It is critically important to generate appropriate mesh to facilitate accurate numerical solution and consideration was given to below factors:

- Mesh should be sufficiently dense but practically computable.
- Grid spacing should be smooth.
- Discontinuities or skewness should be avoided.
- Appropriate choice of the grid should be made.

Ansys workbench has been utilised to generate the geometry of the jet apparatus and further meshing was completed in the meshing tool of the workbench with 400k tetrahedral elements (Figure 14). This mesh supposed to resolve the flow phenomena between the nozzle exit point and the surface of the deflector.

Values of force exerted by the curved surface can be calculated theoretically and from the numerical model and observations are recorded in the Table 2. These values will be compared to evaluate the discrepancies between theoretical and numerical values.

Figure 14: Tetrahedral volume mesh, 400K elements

Table 2 Observation Table

Nozzle Diameter (m)=0.008 m			Flow Area (m^2) =5.0265x10^{-5} m^2	Force exerted by the curved surface=	
Test No.	Velocity (m/s)	Flow Rate (m^3/s)	Velocity^2 (m/s)^2	F_y from equation	F_y numerical model
1					

2					

Anticipated outcome:

Anticipated outcome is discussed in Table 3.

Table 3 Anticipated outcome

Category	Example
Demonstration/Observation based online laboratory example	Hydraulic and Pneumatic circuits
<ins>Anticipated Outcome:</ins> This laboratory was developed mainly to facilitate guided and self-paced learning for students in remote locations who cannot attend the physical laboratory or who don't have access to the physical equipment. After going through this experiment, students will gain the required basic understanding of various components used in hydraulic and pneumatic circuits and how they are connected. <ins>Pilot Study results:</ins> The pilot study was carried out with a small group and the authors received encouraging feedback. The participants reported that these laboratories were quite helpful in understanding the basics of hydraulic and pneumatic circuits and they found the interaction very engaging.	
Remotely operated online laboratory example	3 -phase generation and distribution
<ins>Anticipated Outcome:</ins> This remotely operated physical laboratory was developed to make laboratory access more flexible for the students in terms of time and location. All the students can operate the physical apparatus set up in the EIT laboratory remotely at any time. All the students who are enrolled online or on-campus can gain a deep understanding of 3-phase generation and distribution and resistive and inductive loads. <ins>Pilot Study results:</ins> The pilot study was carried out with a small group of students and the authors have received positive and encouraging initial feedback. Students found this laboratory engaging and very helpful for understanding the basic concept. Moreover, they felt that the laboratory was easy to use and the exercise helped them understand 3-phase generation and distribution.	
Software based online simulation laboratory example	CFD simulation of jet apparatus
<ins>Anticipated Outcome:</ins> This laboratory is a good example of converting a physical instrument into a numerical model using appropriate software so that it can be accessed online and remotely by the students in different locations. This laboratory also mitigates moderate level risk involved while using the physical apparatus and multiple versions can be created without involving higher costs of physical equipment. The experiment can serve as multiple iterations without using important. <ins>Pilot Study results:</ins> The pilot study was carried out with a small group and positive feedback was received from the participants. Some participants noted that the numerical model provided them with nearly the similar experience as using the real equipment.	

All these laboratories were developed and implemented for the first time at EIT and hence only pilot tests were carried out. Detailed student feedback and performance data will be collected and analysed over coming semesters and shared in a suitable future conference.

Conclusion:

The exponential growth in online, communication and IoT technologies have made engaging and effective online engineering education a reality. Online laboratories offer significant opportunities in the world of blended learning making them equal or better to physical laboratories.

The three types of online laboratories discussed by the authors, software-based simulation, remotely operated physical laboratory and demonstration/observation based online laboratory each have several advantages over physical labs such as flexibility, scalability, accessibility, repeatability, cost, resource optimisation and safety. Given the effectiveness of online labs are acutely tied to its interactivity, GUIs are a great way to achieve this. While creating interactive and realistic engineering experiments are still at its infancy, there are many opportunities to be leveraged.

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