Virtual Laboratories in Engineering Education: The Simulation Lab and Remote Lab

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ABSTRACT: Computing and communication technology has had a significant impact on the engineering education system. This technology has improved online and collaborative learning. Besides that, it improves the students learning experiences. One of the distinguishing elements of engineering education is the laboratory requirement. In this paper, we discuss the current trends and key issues in virtual laboratories-simulation environment laboratories and remote laboratories via the Internet. © 2008 Wiley Periodicals, Inc. Comput Appl Eng Educ 17: 108–118, 2009; Published online in Wiley InterScience (www.interscience.wiley.com); DOI 10.1002/cae.20186

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INTRODUCTION

The main function of engineering profession is to manipulate materials, energy and information; thereby creating benefit for humankind [1]. "Doing" is the key in engineering profession. In the early years of engineering schools, engineering was taught in apprenticeship programs [2]. The earliest engineering schools in France and US implement this method in their teaching process [3]. In those years, engineers had to design, analyze and build their own inventions and the focus was clearly on practice [2]. Engineers have to go beyond the theoretical knowledge because in application-based education, it requires not only conceptual understanding, it needs practical knowledge, thus, there are two distinct learning environments in engineering education (classroom and laboratory).

Students can gain theoretical knowledge in the classroom but it is only possible to grasp necessary practical knowledge and experiences in the laboratory. There are many existing systems that enable theoretical courses to be delivered online/Internet. Providing theoretical educational materials is a simple task, where we can use several multimedia tools and editors such as HTML, SMIL, and XML that are available to create courseware [4].

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The biggest challenge facing both institutions and instructors is how they are going to place ''real'' labs on the Internet. Introducing the laboratory learning environment online is a difficult task but with the rapid development of communication technology, it becomes simpler [5]. New possibilities in the way lab exercises are performed include simulation environment lab, automated data acquisition and remote control of instruments online. Currently, there are two approaches to conduct labs online. (a) Simulation and (b) Remote labs. Simulations have been shown to be equivalent to physical lab for explaining and reinforcing concepts [6]. Even so, it provides limited capability for experimentation. The second approach allows the students to work on real equipment and instrumentation, located at a distance via Internet/Online. However, many existing remote labs do not provide the user with a feeling of real presence in the lab [7].

The outline of this paper as follows: First, the objectives of instructional laboratories are presented. Both simulation lab and remote lab are discussed, including brief descriptions of current lab practice. The key points that are to be considered before selecting the suitable lab between simulation and remote labs are presented. Finally, both online labs are compared from several points of view.

THE OBJECTIVES OF ENGINEERING INSTRUCTIONAL LABORATORIES

Considering the three types of laboratories [1]:

(a) Development Lab: practicing engineers go to the development laboratory for two reasons [1]:
First: to answer specific questions enabling the design and development process to continue.
Second: to determine if a design performs as intended, by comparison to specifications, and demonstration of compliance.

(b) Research Lab: the output of this lab is generally an addition to the body of knowledge.

(c) Educational Lab: students apply classroom theoretical knowledge to gain practical experience.

The current ABET [www.abet.org] engineering criteria states that all engineering programs must demonstrate that their graduates have an ability to:

- ''Design and conduct experiments, as well as to analyze and interpret data
- Design a system, component, or process to meet desired needs
- Use the techniques, skills and modern engineering tools necessary for engineering practice.
- Classroom, laboratories, and associated equipment must be adequate to accomplish the program objectives and provide an atmosphere conducive to learning
- The program must include college level mathematics and basic science (with experimental experience) appropriate to the discipline.''

In the ABET Report 1999 [www.abet.org], it is cited that ''. . .regardless the method of educational delivery, both programs (traditional and distance learning) should be consistent with the stated objective of the programs and it is essential that graduates of both programs can demonstrate the same capabilities.''

Thus it is necessary for an online/distance learning institution to provide the same learning environment as traditional learning process.

Problems arise when there is no clear statement of the objectives of laboratory exercises [1]:

First: designing a laboratory experience without clear instructional objectives is like designing a product without a clear set of design specifications. Something useful might result but, it may not be what was really desired and, at best, the process will be exceedingly inefficient.

Second: innovation will be difficult because there are no targets to inspire change and no standards by which the changes may be judged. This last problem has become clear with the advent of programs offering undergraduate engineering degrees, including laboratories, using the Internet or other distance learning technologies.

To help to resolve this problem, ABET organized a colloquy on Learning Objective for Engineering Education Laboratory with a support from Alfred P. Sloan Foundation. Fifty one distinguished engineering educators gathered in San Diego, California in January 2002. They came with 13 learning objectives [4]:

All objectives start with the following: ''By completing the laboratories in the engineering undergraduate curriculum, you will be able to. . .'' [4].

Objective 1: Instrumentation. Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.

Objective 2: Models. Identify the strengths and limitations of theoretical models as predictors of real-world behaviors. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.

Objective 3: Experiment. Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.

Objective 4: Data Analysis. Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.

Objective 5: Design. Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements.

Objective 6: Learn from Failure. Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineer effective solutions.

Objective 7: Creativity. Demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving.

Objective 8: Psychomotor. Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources.

Objective 9: Safety. Identify health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly.

Objective 10: Communication. Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.

Objective 11: Teamwork. Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.

Objective 12: Ethics in the Laboratory. Behave with highest ethical standards, including reporting information objectively and interacting with integrity.

Objective 13: Sensory Awareness. Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.

The objectives cover the range of knowledge in cognitive domain, psychomotor domain and affective domain. As cited in Ref. [1], Objective 1, 2, 3, 4 and 5 are dealing with cognition. Objective 8 and 13 are included in psychomotor domain [1]. The remaining objectives are partly in both cognitive and affective domains. It is necessary for the effective engineer to be exposed with all these three domains.

As cited in Ref. [8], it is generally accepted that some of these 13 criteria may be met as easily online as in a campus lab environment but it is difficult to fulfill psychomotor and sensory awareness.

SIMULATION LAB

Simulations play a vital role in engineering education especially in laboratory exercises. Edwin Link in 1928 developed the ‘‘Link Trainer’’(Flight Simulator), believed to be the first simulation program used in ‘‘Blue Box’’ [1]. The simulator was used to train thousands of military pilots before and during WW II.

Simulators are used in many industries such as aviation, chemical, petroleum, nuclear, and other engineering applications. Finite Element (FEM) structural analysis tools [9] and SPICE, a circuit design and analysis software [eCircuit Center: www.ecircuitcenter.com/spicetopics] have revolutionized the simulation software development for engineering processes.

Online engineering education presents a challenge for educators to convert real to virtual labs, and simulation software has become a vital tool in substituting the physical lab. Simulation environments can train and expose students to practical knowledge, for example ‘‘Virtual Experimentation’’ [10]. Such simulations are widely used on campus and for online/distance learning [http://www.sloan.org/programs/edit_careers.html]. Simulations are well known educational tools in computer technology programs [11].

Engineering educators find simulation attractive because of portability, easy of use, and cost effectiveness [12]. However in a simulation environment, practical knowledge and experience gained by the student depends on the authenticity, constraints and capabilities of the software [13].

Limited pre-designed inputs and outputs in the software restrict the student’s creativity. Suitability and efficiency of the simulation depends on the software criteria. The criteria that discussed in Ref. [14] are as below:

- Modularity: allows to test individual modules easily and to develop applications quickly.

- Multi-platform portability: enables designers to work on separate parts and compile them on one platform.
- Compatibility with existing code: allows incorporating with previous applications, and also with the previous versions of the software.
- Compatibility with hardware: to be able to gather data from different interface hardware.
- Extendable libraries: to let the designer build libraries of low-level routines to link them in higher-level systems.
- Advanced debugging features: to optimize product design and to determine a defect in the code.
- Executables: to avoid alteration, to hide the code or to create standalone applications.
- Add-on packages: indicate the market acceptance of the product and speed the development.
- Performance: to ensure that the end product meets the required performance.
- Intuitive Graphical User Interface (GUI): enables a user to look at it and see what needs to be done.
- Multimedia Capabilities: for future development.

As cited in Ref. [1], simulation laboratories are primarily used for:

1. Pre-lab experience to give students some idea of what they will encounter in actual experiment [1]. It will help students to familiarize with the experiment, improve the skills and able to predict the outcome before performing the experiment in real lab.
2. Substitute for physical lab exercises. It can be used to assess and compare the students' performance between simulations and traditional lab. As cited in Ref. [15], students with simulation experience were able to grasp theoretical knowledge easily when performing experiments in the real lab.
3. Substitution when the system studied is dangerous, expensive or large, and not practical for a typical educational laboratory.

Students can access the software via Web Browser or install it in their PC. Simulation based labs on Internet which use software can be classified in two groups:

a. Processing on each client: simulators of real-lab tools or experiments can be run on students' computers. The software is mainly in JAVA applets run on commonly available www Browsers in an interactive way [16]. The architecture of this class shown in Figure 1.
b. Processing on server: the simulator is run on a server and is accessed by students remotely through the web. The interface is a www browser.

MATLAB/SIMULINK [www.mathwork.com/index], Digi-SIM [http://nicadd.niu.edu/digisim], P-Spice [www.pspice.com] are some important simulation programs used for educational experiments. These simulation programs create a strong foundation for the establishment of simulation environment laboratories in engineering education.

Simulation has been used to illustrate complicated or not easily visualized phenomena, such as current flow, heat transfer and electromagnetic field [17]. Students can design and build a model then submit it to the simulation program to determine their design's characteristics, the output usually represented graphically.

The expressed downside of using simulations for educational experimentation is:

a. Simulation is not a substitute for a real experiment, as the software represents a mathematical model of the real system [18]. Therefore, it does not provide the real results. Proficiency in software use is an important factor in determining the outcome of an experiment, the proficient student likely to achieve better results [15].
b. Revision or adding new experiments in line with changes of syllabus means a revision on overall simulation package, which is not an attractive proposition since it involves high cost [16].
c. The students might ignore the safety procedures and lab ethics because the simulation based labs do not need to consider those aspects [19].
d. Simulation introduces an element of unreality. The student may be less skillful when handling real equipment [19].
e. The simulation based lab limits excitement and learning curiosity, putting the student in a restricted environment of prescribed inputs and restricted parameters [20].

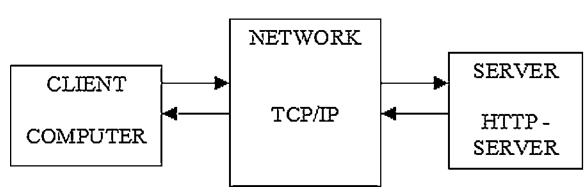

Figure 1 The client processing architecture.

With the current advance in programming and graphical technology (Virtual Reality), the unrealistic issue in computer simulations [1] could be addressed through 3D Simulation Lab [21]. Some engineering institutes are adopting 3D technology in their simulation labs, for example, Geo-technical, Rock and Water Resource Digital Library (GROW) a part of National Civil Engineering Digital Library (NCERL) project [www.grow.arizona.edu/spt-about.php]. It is being developed in the department of Civil Engineering and Engineering Mechanics of University of Arizona. Part of GROW is a Virtual Geo-technical lab created by Muniram Budhu [22].

This virtual lab allows not only for testing the soils but permits the students to explore other tests, which are difficult to conduct in real labs. This virtual lab was created with the following features [22]:

(i) Informing the students.
(ii) Testing the basic knowledge.
(iii) Familiarity with the apparatus.
(iv) Sample/Demo of Experimentation.
(v) Setting up a specimen in apparatus.
(vi) Observation of results.
(vii) Guiding the interpretation of the test results.
(viii) Answer quiz/Test.
(ix) Providing feedback throughout the testing.

Figures 2 and 3 shown some of the features in the 3D Virtual Geo-Technical Lab.

As a result, this 3D virtual lab provides enhanced learning environment [22]. In addition, the students are able to explore more because they can conduct a variety tests beyond the scope of real lab. 3D simulation environment does not prevent the participant from doing an action that could possible cause failure in specific learning scenario. Equally important, the students are able look at the equipment more realistically as the graphics are in 3D. Therefore, 3D lab is a better choice compare to 2D but the cost of design and development is relatively high [23].Examples of currently practiced simulation labs are listed in Table 1.

ONLINE REMOTE LAB

Distance education method adopted by many higher education institutes around the world [24]. In the area of engineering education, experimental/laboratory work becomes a major concern as engineering disciplines focus more on solving problems in the ''real-world.'' Practical exercises are essential in order to develop skills of how to apply theoretical knowledge in real-world problems [25].

Simulation based labs cannot provide a ''feel'' for real things. Students need to use real devices and execute commands on real tools to gain necessary practical skills. Distance education institutes need to find a solution to provide the students with meaningful and relevant practical experiences while at the same time it being online.

A system that adopts computer-based technique to interface the students with the physical world is needed, a laboratory that could provide access through a Web browser to the real equipment in laboratory. This lab enables student to send commands, which can be pre- processed on the student's side. Then, it will goes through the server and execute the experiment in the real lab on real equipments. The results of the experiment will be appeared at the student's side.

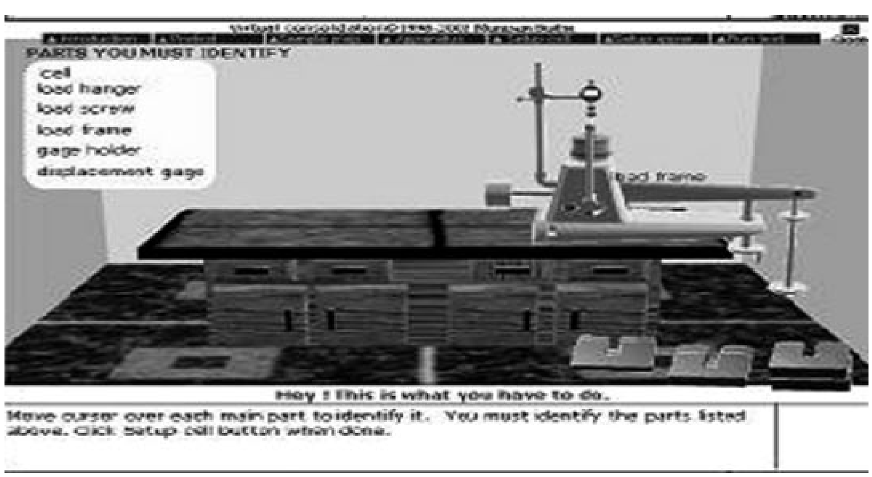

Figure 2 Identification of various apparatus [22].

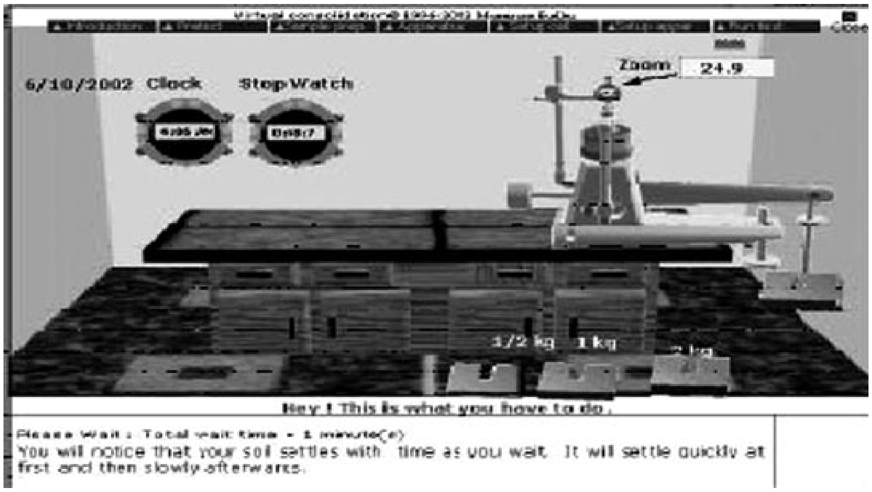

Figure 3 A virtual consolidation test in progress [22].

The first such remote laboratories are control and robotic labs [26], other remote labs have become more common in other engineering fields. Most of these new labs utilize *LabView* web server that developed by National Instruments [14].

Internet technology allows the institute to provide students with distance access to the actual laboratory tools and give them the essential practical skills. As cited in Ref. [27], the application areas of remote laboratories are:

1. Shared Remote Lab: if the equipment is very expensive, the students could share and access to the equipment through remote lab.
2. Localized Remote Lab: the institute could establish a remote lab that can be accessed via the Internet to perform experiments at anytime, helping students re-do experiments carried out earlier, enhancing their practical skills.
3. Distant Remote Lab: this kind of remote laboratory is useful for distance learners.
4. Technical Review Lab: this lab will be useful for professionals who would like to test a particular system or equipment from their desk.

In order to conduct an experiment there are a few components required to build a complete web based remote lab [28] as shown in Figure 4.

1. Client Stations: basically a Personal Computer with Internet access.
2. Internet: Intermediate System/Network that connects Client's Station and Remote Lab Server.

Table 1 Examples of Simulation Lab

Software	Applications/subjects	Website	Institution
20SIM	Electrical/Mechanical/ Hydraulic System	www.20sim.com	Twente University Holland
Berkeley-Madonna	Chemical Reactions/ Dynamic System	www.berkeley-madonna.com	University of California, Berkeley
DYNAST	Mechanical and Dynamic System	http://icosym-nt.cvut.cz.cacsd/msa/online	Czech Tech. University
HOPSAN	Hydraulic System/Fluid Flow	www.flumes.ikp.liu.se	Linkoping University
C++Sim/JavaSim	Computer System	http://javasim.nd.ac.uk	Newcastle upon Tyne University
Stroboscope	Construction Operation	http://strobos.ce.vt.edu	Virginia Tech
WARPED	VHDL Analyzer (Digital Electronics)	www.ececs.uc.edu/~paw/warped	Cincinnati University
SHIFT	Robotic/Automated System	http://path.berkeley.edu/shift	University of California, Berkeley

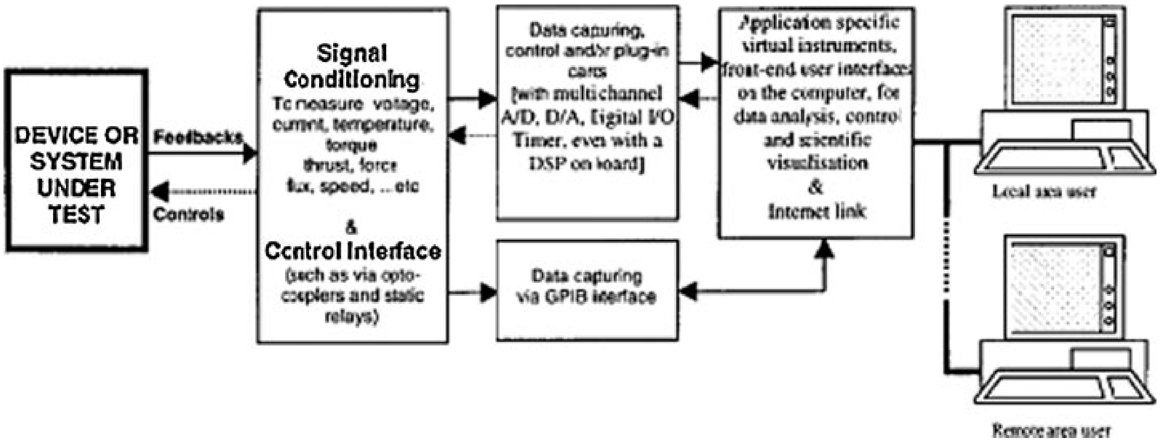

Figure 4 Remote lab architecture [14].

3. Remote Lab Server: server(s) used to provide access to the experimentation units.
4. Experimentation Unit: a set of equipments and devices, which is used to carry out experiment.
5. Instrumentation Unit: instruments that used to measure the readings from the experimentation unit/provide real-time measurement of the experiment.

A complete remote laboratory environment raises some issues:

1. Hands on experience: there should be a clear view on the monitor from the video camera of all devices and instruments used in the experiment. The settings should be suitable for all students with different level of skills. There must be an automatic error detection and notification system, so students are able to understand mistakes made at each step. The measurement result should be provided in a same form as the real measurement devices. The display of an oscilloscope, multi-meter, power generator etc. on the PC should look like the real device.
2. Flexibility and reliability: the access to the remote lab must be flexible, there should be no restriction in time and place. The students can perform the lab exercise at anytime and anywhere. It means the remote lab should be open 24 h everyday to be accessed from anywhere. The devices, measurement instruments and server in the remote lab should be highly reliable—there should not be faults or breakdowns in the system.
3. Cost: depends on the price of the devices, instruments, servers and software that are used to build a complete set of remote lab, additionally the number of students using the system. Students should not bear extra cost such as software or other devices, the institution providing related software via the Internet. The systems should be maintained by qualified technicians to guarantee reliability.
4. Learning experiences: it is essential that students enjoy and gain knowledge from the remote lab exercise. There should be a demonstration before the student carried out the lab exercise to give them confidence. Equally important, the students must be able to discuss online the experiments with other students and instructors.

Practical Experimentation by Accessible Remote Laboratory (PEARL). PEARL was established to develop a flexible system enabling students to conduct real-world experiments remotely. Led by Open University, UK with partners from Trinity College Dublin, Dundee University, Open University World Wide, University of Porto and ZENON [PEARL Project: http://iet.open.ac.uk/pearl], the project was aimed at science and engineering subjects at university level. This remote lab gave special attention to disabled students [29]. The system integrates a remote controlled lab, collaborative learning environment and accessible user interface sub-system. It has special tutor guidelines for implementing experiments. At the University of Porto in Portugal, there are three types of remote experiments designed for digital electronics lab. One of the experiments is Introductory to Logic Design. This experiment is supported with a hard-wired logic workbench, where students deal with the counters, shift register, finite state machine, etc. [30]. Programmable Field Programmable Gate Array

(FPGA) is used to conduct this lab exercise with the procedures described as follows [30]:

1. Design the circuit and provide the programming file.
2. Verify and debug the circuit.
3. Connect the remote lab server.
4. Upload the code, reset the remote hardware and transfer the programming file to the hardware (FPGA).

The user interface for this experiment is illustrated in Figure 5 and the remote hardware used in this experiment depicted in Figure 6.

From Ref. [30], it is stated that this remote lab provides an interesting remote experimentation that gives an awareness of practical issues, which would not occur in a simulation lab. Equally important, the students could access the system from home with minimum requirements and dealt with real data and real time output. Examples of online remote labs are listed in Table 2.

SELECTION AND COMPARISONS BETWEEN ONLINE LABS

The suitability and selection of the type of lab depends on the educational goal of the lab experiment. Therefore, computer, software and electronics engineering experiments are more likely to be performed through simulation, while power, civil and control engineering experiments are suitable to be carried out through remote lab [31]. Institutions should focus on a few key points before selecting the suitable online lab (Table 3).

Pedagogical Needs of the Experiment

Some may argue that simulation lead to oversimplification of an experiment and it might leave out some important aspects of real thing [31]. It is very important to identify the objectives and expected outcomes of an experiment in order to select the suitable online lab. If the experiment needs the students to be exposed to real data, interaction with real equipment and calibration, the remote lab should be preferred. Simulation based lab is suitable if the experiment needs the students to gain more on theoretical knowledge and conceptual understanding of a particular experiment [32].

Economical and Resources Factors

The institution should look at the financial and resources requirements before choosing between the remote and simulation lab [33]. Space, financial support and sufficient technical assistance are critical in establishing simulation labs, it is important to consider the price of simulation software, period of license and availability of expertise to change and develop the simulation software following changes of syllabus and technology related to the experiment [34].

Participants

It is necessary to identify the types of students and their needs, especially if the institutes offering distance education. Because, typically, there are two types of students who enrolled as distance learners:

a. *Novice*: they should be exposed with real thing to build practical skills. Remote lab is preferable

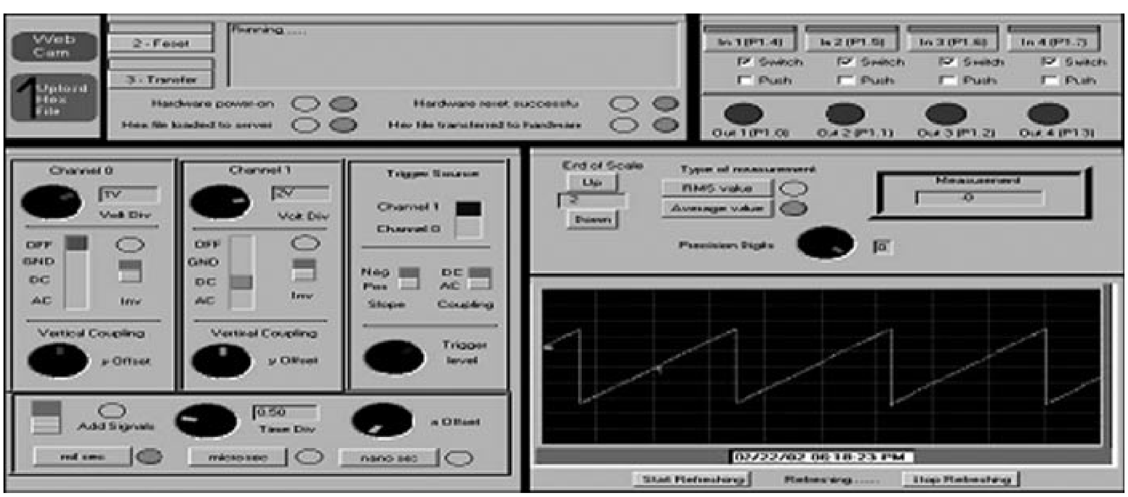

Figure 5 User interface [30].

Figure 6 The FPGA board used to support hardwired logic experiments [30].

at this level because it helps to gain real experiences.

b. *Mature*: students who have several years working experience might lack learning capabilities [35]. The simulation environment, with good pedagogical features can re-ignite their learning curiosity, with well-designed software providing effective explanations of theoretical concepts [35].

Realism

Remote labs can get very close to real hands-on experience but with simulation labs sense of reality and actual control are considerably lower, however 3D simulation labs are more realistic as the graphics are in 3D [21]. High realism in remote lab depends on the quality of the image on the PC screen.

Freedom of configuration and experimentation are limited in simulations software. In remote lab, it is limited by pre-configured options in Graphic User Interface (GUI). Therefore, remote lab needs special

Table 2 Examples of Online Remote Labs

Institute	Subject	Website
University of Tennessee	Control System Lab	http://chem.utc.edu/webres/stations/controlslab.html
Carinthia Technology Inst.	Electronics Lab	http://online-lab.net/rel/index.htm
University of Leipzig	VIPRATECH-Chemical Engineering	http://leipzig.vernetztes-studuim.de
Uni. Of Western Australia	TELEROBOT-Mechanical Engineering	http://telerobot.mech.uwa.edu.au/
North Carolina State University	Civil Engineering-Structural Engineering	http://pxi-112mn.ce.ncsu.edu/
MIT	iLab-Chemical Engineering	http://heatex.mit.edu
University of Colorado	ROCK-Optical Engineering	www.tech.uh.edu/rock/remotelabs.php

Table 3 Comparisons Between Physical, Online Remote and Simulation Labs

Issue/parameter	Real Lab	Remote Lab (Online)	Simulation Lab
Cost	High	High	Low
Equipment and facilities	Need equipments and space	Need equipments and space (relatively small)	No
Hands on experience	The best exposure	Close to real lab	Completely virtual
Reality and actual control	Very high	Reasonably high-depends on GUI [http://roma.unisa.edu.au/resources/netlab]	Low for 2D Realistic for 3D [22]
Accessibility	Limited	Limited-depends on timetable	Not limited
Instructor's Supervision	Instructor present during lab session	Online chat/e-mail	Online chat/e-mail
Support and Teamwork	Support from lab assistant and fellow team members	Independent	Independent
Educational benefits	Real experiences and practical skills	Interaction with real equipment via online	Good exposure to conceptual learning
Safety	Yes	None	None
Maintenance	Equipments	Equipments and software updating	Software updating

GUI to give a sense of reality [http://roma.unisa.edu.au/resources/netlab].

Accessibility

Simulations give freedom and flexibility to the students to perform experiments at anytime and anywhere limited only by number of software licenses. The students have to queue and follow the schedule to conduct experiments in remote lab. The queue time depends on number of users and experiment sets provided.

Student's Interaction and Instructor's Support

Both remote and simulation labs lose the normal interaction that can occurs in real laboratory since the students are isolated from other students and instructors [36]. In real labs, assistants or supervisors will be present to answer any questions raised by the students. This could be substituted by online live chat or discussion with instructors and fellow students during the lab exercise in online lab but it will be not practical if the student performing experiment outside the working hours. Thus, it is necessary to developer to provide FAQ list of the experiment in which the students could refer in order to answer their query [37]. In addition, a discussion board specifically for each experiment should be provided, where the students could voice out their opinions [38].

The main comparisons between each type of laboratory are summarized in Table 1.

CONCLUSION

Computer and communication technology have made online learning an achievable goal in engineering education. Online labs offer vast advantages in engineering laboratory education and become an alternative to physical labs.

The simulation lab is a simplified version of a system, and though much criticized for not giving sufficient real experiences, there are a several advantages over real labs, such as flexibility, explanation of theoretical concept, and repetition. The simulation environment is much improved by implementing 3D.

The remote lab allows users to control and perform experiments on real equipments via Internet. The benefits of the remote lab are a mixture real and simulation lab advantages. The effectiveness of the remote lab depends on the user interactivity. Text based user interface would be a poor replacement for physical lab. Hence, a realistic GUI is preferable in this lab.

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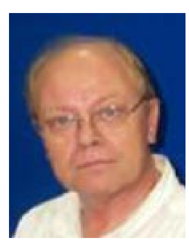

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