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Alternative Approaches to Undergraduate Engineering Laboratory Experience for Low-income Nations

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1. Introduction

The engineering profession requires a foundation of proficiency in conceptual understanding, as well as proficiency in design, problem solving and analytical thinking [1], [2]. Undergraduate laboratories provide an opportunity for students to practice these skills through conducting experiments and data analysis [3]. Laboratories also help students develop professional, social and teamwork skills [4], improve practical/psychomotor skills [5], [6], and become familiar with scientific inquiry and safety procedures [4], [7]. Hands-on laboratories also provide an opportunity for students to analyse unexpected data, which could result from instruments/apparatus malfunction, noise or other uncontrolled variables [6]. In other words, experimentation teaches students both the power and limitations of theories through data obtained from laboratory work [8].

The downside is that laboratories are very expensive to operate in terms of facilities, resources and staff time [7], [8], [9], which make them unaffordable for some institutions [10]. Laboratory costs are even more out of reach for universities in low-income nations, including many universities in Africa. For example a typical laboratory workstation for electrical and computer engineering costs approximately $5,000 USD [11]. A typical university laboratory requires multiple stations, raising the total equipment cost per laboratory to $100,000 USD for 20 laboratory working stations, which is often not affordable for some universities in low-income nations [11]. Therefore, many undergraduate laboratories do not have proper equipment, or they are underequipped [12], [13], which forces students to perform experiments in larger groups [14]. This usually results in one person performing the experiment, while others observe [12], [14], which diminishes some of the learning value ascribed to laboratory experimentation. Additional challenges include inadequate physical spaces and limitations on skilled human resources for undergraduate laboratories at many universities in economically impoverished areas of the globe [12]. Given this reality in many parts of the world, new and innovative approaches are required to enhance access and learning in low resource settings.

New technologies provide opportunities for students to conduct experiments, while substantially reducing the costs associated with traditional laboratories. Virtual and remote laboratories, collectively known as VRLs, and portable hardware platforms can be viewed in this light. This paper provides an overview of each of these methods, and the extent to which they can be used to supplement or substitute for laboratory experimentation in the context of undergraduate engineering education in low-income nations, with an emphasis on universities in African countries. A synthesis of the available literature is provided with some contextualisation through interviews conducted at one university.

2. Methods

The research conducted in this paper is part of a larger project at the University of Toronto that explores engineering education with a focus on Africa. The project is Engineering Education for Sustainable Cities in Africa, which was started in 2015 with funding from the Dean's Strategic

Fund in the faculty of Applied Science and Engineering. As part of the project, the research team has carried out site visits to 29 institutions across 11 countries in Africa varying between traditional universities and emerging institutions with a focus on sustainability content in engineering curricula; employment trends of engineering graduates; online and distance education; and skills relevant to rapid urbanization in Africa. The research protocol has been approved by the Research Ethics Board at the University of Toronto, under Protocol ID 33167. Data for this paper were gathered through interviews conducted with faculty and students at Makerere University (Uganda) regarding remote laboratories. The questions explored the disciplines that adopt remote laboratories, the structure and sharing of these laboratories, advantages and disadvantages and the costs of set up, operations, and maintenance of these laboratories, in addition to assessments regarding the learning, if any.

3. Discussion

3.1 Remote and virtual laboratories

Remote laboratories provide access to real laboratory equipment and real data via the Internet, regardless of where the students are located geographically [3], [15]. They also allow students to perform experiments at their own pace [19], while focusing on the experimental observations and results, rather than the physical manipulation of instruments or techniques [7], [20]. Remote laboratories are also suitable options for experiments that might be too expensive for students to perform physically [3], for distance learning [3], and for students with mixed-abilities and special needs [21]. They also provide an opportunity for research and education collaborations among institutions around the world [21]. Remote laboratories have most often been used to teach electrical and mechanical engineering [22].

Virtual laboratories (or simulations) are computer software/models, which provide simulated data [3], [15]. They provide an opportunity to demonstrate unobservable phenomena such as electromagnetic fields, laminar flow in pipes, heat transfer, and electron flow [5], [7], [10], [16], [17]. Virtual laboratories also allow students to conduct more experiments faster and cheaper compared to hands-on laboratories, and repeat them as needed [5], [6], [7]. They also provide an opportunity for students to explore “what if” situations [12], by changing variables that are unrealistic or impossible to change in the real world [7].

While the use of VRLs has increased across a variety of domains and educational disciplines [15], the effectiveness of these approaches compared to hands-on laboratories has not been firmly established [4], [23]. Lack of direct interaction with real apparatus, lack of authentic settings and the distraction caused by the computer are among the criticism of VRLs [23], [24]. Another criticism, specifically for simulations is lack of appreciation of the limitations of theories or sources of errors [3]. Given that each laboratory modality has its own advantages/disadvantages, some have argued that direct comparison between them is not appropriate [4], [19]. Rather, the differences should be acknowledged, and tailored to specific learning outcomes to enhance the learning experience of laboratories [19]. Some researchers have also shown that combining the different modalities can increase the conceptual understanding of students in laboratories [25-28]. The next section presents some of the examples of VRLs, specifically within the low-income nations.

3.1.1 Remote laboratories: iLabs

iLabs are an example of remote labs, which were first developed by Prof. Jesus A. Del Alamo at the Massachusetts Institute of Technology (MIT) in 1998, for experiments in microelectronics [29]. A web service infrastructure called the iLab Shared Architecture (ISA) was then developed to facilitate development of iLabs [29]. ISA is a three-tier architecture consisting of a lab client, a service broker and a lab service [29]. The lab client is the student interface, where students can access the experiments. The service broker is necessary for authentication, authorization, data storage and scheduling services. The lab service interacts with the instruments, and provides results through the service broker [29]. This infrastructure allows students to perform two types of experiments: batched experiments in which the parameters are first set before the execution, and interactive experiments in which the parameters can be monitored or controlled during the execution [29]. iLabs offer experiments in control theory, circuits, microelectronics and physics [30]. They can provide unprecedented access to scientific resources among many institutions in low-income nations, as well as providing an opportunity to share laboratory costs among universities. However, Internet connection quality such as bandwidth and speed, as well as access to computers can pose a challenge for the successful implementation of iLabs in those countries [29].

3.1.2 MIT iLab project in Africa

The most prominent example of iLabs use in Africa is the Carnegie Corporation supported collaboration of MIT with three African universities: Obafemi Awolowo University (Nigeria), Makerere University (Uganda), and the University of Dar Es Salaam (Tanzania) [31].

An interview was conducted with a few faculty members and students at Makerere University, in June 2016, regarding iLabs. Makerere University has no direct link with MIT anymore, but has been developing its own iLabs (iLabs@Mak) based on the infrastructure adapted from MIT, using National Instruments Educational Laboratory Virtual Instrumentation Suite (ELVIS). ELVIS is a small device, which gives the opportunity to perform tests using function generators, oscilloscopes and dynamic signal analyzer [31]. The iLabs cover experiments in telecommunication, electrical and computer engineering courses. The university cannot provide equipment such as oscilloscope and function generators to every student all the time, and therefore, students have to preform laboratories as a group. iLabs serve to complement the hands-on laboratories, providing an opportunity for every student to perform laboratories on their own. Students can also have access to circuits that are otherwise not available. Currently, iLabs@Mak has become a hub, where students at other universities such as Busitema University (Uganda), Mbarara University of Science and Technology (Uganda), and University of Rwanda can also access them.

Some challenges that hamper broader adaptation of iLabs were surfaced through our interviews. For example, it was mentioned by the faculty representatives that students are usually not motivated to use iLabs, because of challenges associated with the Internet connection, bandwidth and electricity connections. Yet another challenge for the faculty members is fair assessment, as students can login and perform experiments for one another.

Makerere University currently has 20 ELVIS boards, which were provided through a grant from MIT. However, each board is approximately $3000, and hence costly, making it unaffordable for many universities. Therefore, Makerere University is trying to move away from ELVIS to Open Labs Platform, which includes open source based hardware architecture and software. This platform will enable the expansion of the application of iLabs, and cover other disciplines such as civil and mechanical engineering.

Makerere University intends to assess the effectiveness of iLabs in terms of learning outcomes, as few studies of this currently exist in the literature within the context of low-income nations. One such study carried out at Obafemi Awolowo University (OAU), evaluated the effectiveness of MIT Dynamic System Analyzer iLab in 2010 [32]. A survey conducted right after students performed experiments using iLabs revealed that students had positive opinions about them, and they thought that other courses should also include iLabs. Disadvantages mentioned by students included the requirement to own a personal computer and access to a reliable Internet connection [32]. However, the positive "impressions" seemed to dissipate over time, as a year after, more than a fifth of the students did not think of iLabs as useful anymore. An explanation provided by the authors is that the students could see the failings of iLabs more clearly after a year. Moreover, students mentioned that they could not actually "see" the system being tested, as there was a schematic interface. A recall test was also administered a year after, where students were asked to recall the laboratory procedures. The students were randomly assigned to two groups. One group was asked to reflect back on the traditional laboratories, while the other was asked to reflect back on iLabs. No difference in test scores was found between the two groups, and therefore it was concluded that iLabs are as effective, or ineffective, as traditional laboratories [32].

3.1.3 Examples of virtual labs

Virtual laboratories have been developed for many engineering disciplines, such as electrical, chemical and civil. Unlike remote laboratories, there is no real equipment associated with virtual laboratories. Rather, they provide simulated data based on mathematical equations [3], [33]. To the best of our knowledge, no significant example of virtual laboratories in low-income nations in Africa has been reported. However, greater uptake has occurred elsewhere; one of the most significant resources of virtual laboratories in a low-income nation is the Virtual Labs Project in India. This project is an Open Educational Resource (OER), developed by twelve Indian Institutes of Technology (IIT), which can be accessed through the Internet (http://vlab.co.in/index.php), free of charge [33]. The aim of this multi-Institution multi-discipline project is to offer laboratories for universities that do not have physical laboratories, as well as, to complement hands-on laboratories at universities with physical equipment. Students can perform the labs at their own pace at any time and any place [33]. There are over a hundred laboratories covering the following areas: Electrical and Communication engineering, Computer Science and Engineering, Electrical Engineering, Mechanical Engineering, Chemical Engineering, Biotechnology and Biomedical Engineering, Civil Engineering, Physical Science, and Chemical Science.

The project's goal is to ensure that these virtual laboratories require minimum hardware and bandwidth. In addition, this resource provides a complete Learning Management System (LMS), by offering supplementary documents such as lab manuals, video lectures, web resources, animated demonstrations, and quizzes [33]. The virtual laboratories undergo standardized evaluations by experts from different Indian Institutes of Technology. In 2013, it was reported that about 100 engineering colleges in India were using these online resource [33].

Table 1. Comparison Between Remote laboratories, Virtual Labs and Portable Hardware Platforms.

	Remote Laboratories	**Virtual Laboratories**	**Portable Hardware Platform**
Type of Experiment	Access to real equipment using the Internet	Virtual/simulated experiments	Real physical equipment
Type of data	Realistic Data	Idealized Data	Realistic Data
Requirements	Hardware Components, Computers Internet	Simulation program Computers Internet	Physical platform Computer
Cost	Medium	Low	Varies
Scalability	High	High	High
Disciplines Covered	Limited (electrical/mechanical engineering mostly)	Wide range of disciplines	Limited (Electrical/mechatronics Robotics)
Examples in low-income nations	iLabs at Makerere University	Virtual Labs Project in India	MS-IOBoard at AAiT and iOTech-Hu (Ethiopia)

3.2 Portable Hardware Platforms

Portable hardware platforms can provide real hands-on experience at a lower cost compared to hands-on laboratories. An example of a portable hardware platform is the Mobile Studio Board (MS- IOBoard^{TM}), developed at Renselear Polytechnic University a decade ago. The Mobile Studio Board provides similar functions to standard laboratory equipment such as oscilloscope, function generators, power supplies and voltmeters. When coupled with the Mobile Studio Desktop^{TM} software, it provides an opportunity to perform hands-on exploration of electrical engineering principles, which would otherwise cost $5,000 using conventional laboratories [11] This platform has been successfully used at two universities in Ethiopia: Addis Ababa Institute of Technology (AAiT) and Hawassa University Institute of Technology (iOTech-HU) in collaboration with Morgan State University in the United States. The results have been very promising as the students at AAiT and iOTech-HU indicated that the use of Mobile Studio provided an opportunity to tackle more challenging topics and expand the scope of their capstone design projects [11]. In addition, the electrical engineering departments are able to accommodate fewer students (4-5) per station by adding ten new Mobile Studio Boards to their laboratory workstation benches [11]. Other versions of the Mobile Studio Board have been developed, and are currently being used in universities across the world such as India, Greece, Austria, Germany, Mexico, and Malaysia.

There are other commercial kits/devises that while still used in the context of more conventional laboratories, are space saving and scalable in low-resource settings. Commercial firms operating include, Analog Devices Inc (U.S.A.), Digilent (U.S.A.), Quanser (Canada), Educational Control System (U.S.A), and Feedback (U.K.). Their products aim to provide an opportunity for students to gain hands-on experience in disciplines such as control engineering, robotics, electrics and electronics, mechatronics, and telecommunication. For example, Analog Devices Inc makes two portable laboratory instrumentation kits called ADALM 1000™ that cost less than $100. Digilent sells a similar product called Analog Discovery 2™ for around $300. QUBE™-Servo portable platform from Quanser costs about $4,000 and allows students to conduct experiments relevant to control engineering. Quanser is approaching universities in Africa, but to date broad uptake is not evident.

4. Reflections

Considering that hands-on experience is almost unrealistic in low-income nations mostly because they are cost prohibitive, the VRLs and portable hardware platforms could provide a tremendous opportunity to complement or replace hands-on laboratories. However, as the results of our analysis have shown there are still limitations associated with each of these methods (Table 1).

For example, there has been an increased interest in development of remote laboratories [34], [35], [36]. However, to the best of our knowledge, these remote laboratories have not found a place in African universities, with a few exceptions such as Makerere University, Obafemi Awolowo University and the University of Dar Es Salaam. Some contributing factors include poor Internet connection, unreliable power supply and cost of equipment. Another limitation of remotes laboratories is the limited disciplines covered as most of them are related to electrical experiments. Virtual laboratories are easier to develop than remote laboratories, and could cover more disciplines. There is a general agreement though that simulations cannot completely replace hands-on laboratories, since they only provide simulated and idealized data. But, with the advancements in technologies, more realistic simulations might be developed which could closely mimic real situations and equipment, so that students do not know if the back-end is a software engineering program or actual equipment [3]. Similar to remote laboratories, virtual laboratories have also not been taken up in African universities, compared to for example in India. Again, one reason could be the lack of reliable Internet connections or electricity. Portable hardware platforms are another method with potential benefits for low-income nations. They could be shared among universities since they are portable, reducing the costs for each individual university. Still, a constraint with them is the limitation in the disciplines covered.

Therefore, there seems to be a need for yet a more cost effective, scalable solution for students to perform laboratories in various engineering disciplines in low-income nations. For now, it seems that a combination of these methods might be a feasible solution, especially for electronics/electrics disciplines. Universities can share portable experimentation technologies, or even the hands-on laboratory facilities, complemented by either simulations or remote laboratories. The combination of the modalities could support different types of learning outcomes and learning styles, and hence might be more effective than using any single modality.

Future research could involve determining and addressing factors contributing to the lack of uptake of virtual laboratories, which could be beneficial for other engineering disciplines, such as chemical, mechanical and industrial engineering, as virtual laboratories could cover those disciplines. In addition, effectiveness of each of the methods in terms of learning outcomes and student perceptions should be evaluated within the context used. It is important to determine the strength of each of the methods in achieving the desired learning outcomes.

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