# IMPLEMENTING REMOTE LABORATORIES WITH THE ILAB ARCHITECTURE: THREE CASE STUDIES FROM OBAFEMI AWOLOWO UNIVERSITY, NIGERIA

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**Abstract**

A number of remote labs based on the iLabs Architecture have been developed and used for credit awarding courses in Obafemi Awolowo University (OAU), Nigeria. These include the Op-Amp iLab, Logic Design iLab, and Robotic Arm iLab. The Op-Amp Lab allows students to access a small operational amplifier circuit hosted in OAU, and with the aid of switching matrices, reconfigure the circuit, inject waveforms, and see the resulting output signals. The Logic Design Lab is built around a Field Programmable Gate Array (FPGA) chip that students can reprogram from afar using the VHDL, a hardware description language. The Robotic Arm iLab is a control engineering laboratory in which students can remotely control a robotic arm located in OAU. Video feedback through BroadCam Video Streaming Server and Livestream (www.livestream.com) allows users observe and measure the robotic arm's response to their commands. In our paper, we describe the iLab Batched and Interactive architectures and describe three iLabs developed in OAU in detail. Emphasis is placed on technical details and design choices made in developing these labs. We also discuss other aspects of iLab development and use and dwell on issues that could hinder or accelerate the adoption of remote laboratories in developing countries.

***Keywords: User system, Service Broker, Lab Server, iLab, rlab.***

## Introduction

When applied within science and technology (S&T) curricula, experimentation is supposed to allow students to develop skills in any combination of up to 13 distinct categories [1]. Students' skills are to be tested or developed in the areas of instrumentation, modelling, experimentation, data analysis, design, learning from failure, creativity, psychomotor, safety, communication, teamwork, lab ethics and sensory awareness.

Three main architectural elements are required for this to take place. These are the student, the system-under-test (including associated test equipment), and the laboratory, which is a location or means though which the student can access and manipulate the system-under-test (SUT). Arguably, a fourth architectural element, a lab instructor or lab manual, could be included.

Traditionally, to work on the SUT, students need to be physically present in the laboratory. In recent years however, a set of techniques and tools have made it possible for the student to access laboratory hardware without being at the same physical location or time as the equipment. Such a laboratory in which there is a spatial or temporal displacement between the student and the system under test is generally referred to as a remote laboratory [2] or "rlab". Rlabs have been facilitated by the availability and capability of communication facilities, generalization of computer use for data acquisition [3] and control of real processes, and rapid advances in internet technologies.

One of the prominent platforms for remote laboratory development is the iLab architecture, developed by the Massachusetts Institute of Technology (MIT) [4]. As this platform has evolved, it has spawned three forks, catering for three different categories of experiments: batched experiments, interactive experiments and sensor experiments [5].

*Batched experiments* are those in which the entire course of the experiment can be specified before the experiment begins. The Obafemi Awolowo University (OAU) Op-Amp Lab [6] and the OAU Logic Design Lab [7] are two examples of this. *Interactive experiments* are those in which the user monitors and can control one or more aspects of the experiment during its execution. Examples include MIT's online Heat Exchanger [8] and OAU's Robotic Arm Lab [9]. *Sensor experiments* are those in which users monitor or analyze real-time data streams without influencing the phenomena being measured.

This paper is organized as follows: the next section describes the batched and interactive architectures. Then we describe the iLabs developed in OAU. Followed by a discussion of the OAU experience with three case studies: the Op-Amp iLab, the Logic Design iLab and the Robotic Arm iLab. Then describes other aspects of iLab development and use as well as other issues that could hinder or accelerate the adoption of rlabs on the African continent.

## iLab Architectures Used in OAU iLabs

### *The Batched Architecture*

The batched version of the MIT iLab shared architecture consists of three tiers (Figure 1): a Lab Server, a Service Broker and a Lab Client (or Client for short). The remote experimentation setup and associated equipment are coupled to a computer with Internet access. This computer allows configuration instructions to be passed to the equipment from a remote student's computer. The combination of the equipment, computer, and software running on the computer define the Lab Server tier (also sometimes called the Server tier).

The student who desires remote access to the Lab Server must make use of software that is referred to as a Client Application, or Lab Client, forming the second tier.

A third tier is implemented by having a machine on the student's network (or sometimes on the server network) serve as a proxy for all interactions between the student and the Server. This middle proxy tier, called the Service broker, is responsible for the authentication of users and serves as a go-between between the first and second tiers. The Service Broker is

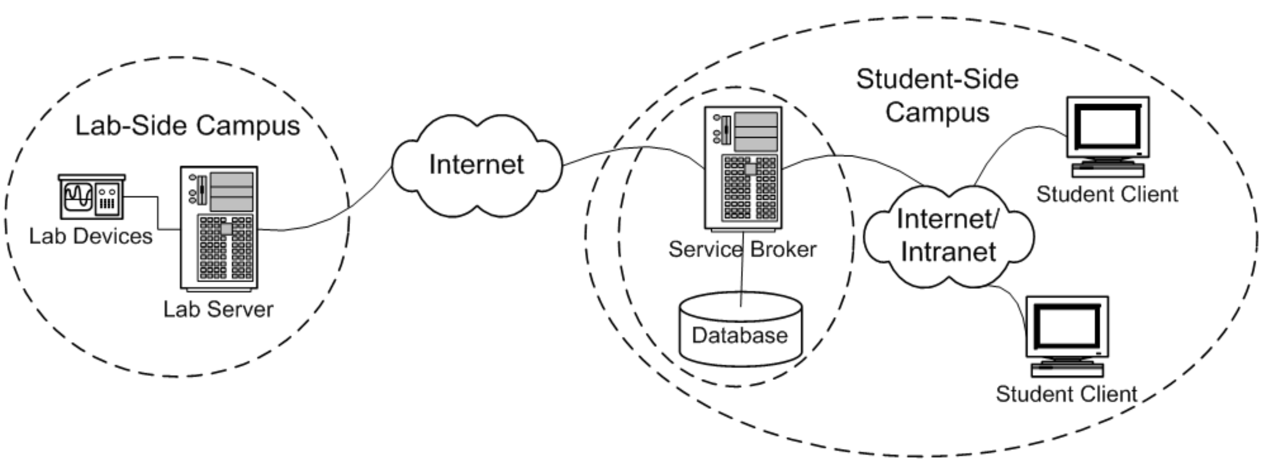


Figure 1: Topology of the Batched iLab Architecture [5].

backed by a standard relational database such as SQL Server™ or Oracle™. The student's Client communicates solely with the Service Broker, which forwards experiment specifications to the Lab Server [5]. The Lab Server communicates solely with the Service Broker, and is never in contact with the student – indeed, it never gets to know which student performs which experiment.

To perform a batched experiment, i.e. experiment launched using the batched architecture, a student logs onto the Service Broker (SB). The SB authenticates the student, determines the student's level of access to the Lab. The SB presents the students with some options based on his level of access – typically, the student is presented with a set of experiments which his level of access permits him to carry out. The student selects an experiment he wishes to perform and the client application for that experiment is launched. The student makes his specifications and sends them "to the lab". In reality, they are sent to the SB. The SB then contacts the Lab Server (LS) on behalf of the student, presenting the experiment specifications. The LS parses the specifications for errors, and if none is found, carries the out the experiment. It then returns the results (or an error message if an error was found in the specifiations) to the SB which passes them on to the student's client and/or stores them till a later time when the student requests for them.

If several students are logged on to the SB at the same time and make submissions of experiment specifications, the SB passes these specifications on to the LS on a first-come-first-served basis. Hence, the experiments are performed in batches – thus the name batched architecture. A corollary of this is that though a student has submitted an experiment specification to the lab, he may not receive the result from the lab till much later – until the experiment submission reaches his turn and the LS performs his experiment and returns his experiment results. Hence, he can submit the experiment specification to the lab, log off the SB and return later to request his result from the SB.

The SB ensures that only the barest minimum of data is actually exchanged over the internet thereby allowing efficient bandwidth utilization [6]. Due to this optimal use of bandwidth, the batched architecture has been particularly useful in OAU, which has bandwidth constraints just like most other African universities.

### *The Interactive Architecture*

Roughly speaking, the interactive iLab architecture also comprises three tiers: a Lab Server, a Service Broker and a Lab Client. In reality however, the interactive architecture comprises six tiers: an Interactive Lab Server (ILS), an Interactive Service Broker (ISB), a User-side Scheduling Server (USS), a Lab-side Scheduling Server (LSS), an Experiment Storage Server (ESS) and the Student Client on the user side (Figure 2).

Interactive experiments are experiments in which one or more of the experiment parameters are made available to the student for real-time control. Hence, in an interactive experiment, the user interacts directly with the lab server such that he can monitor the experiment setup's response to his specifications and make changes to his specifications while the experiment is going on. A webcam on the lab side enhances this.

While performing an experiment, a student interacts directly with the lab hardware in real time. To avoid a situation where more than one student attempts to assert control over the hardware, students are required to schedule lab sessions before hand. Two scheduling servers are used. One scheduling server is placed on the lab's side to enable the lab owner allot time blocks to different user systems and enable him to schedule downtime for maintenance. The second scheduling server is placed on the user system's side to allot time blocks to individual students who log on and request access to the lab.

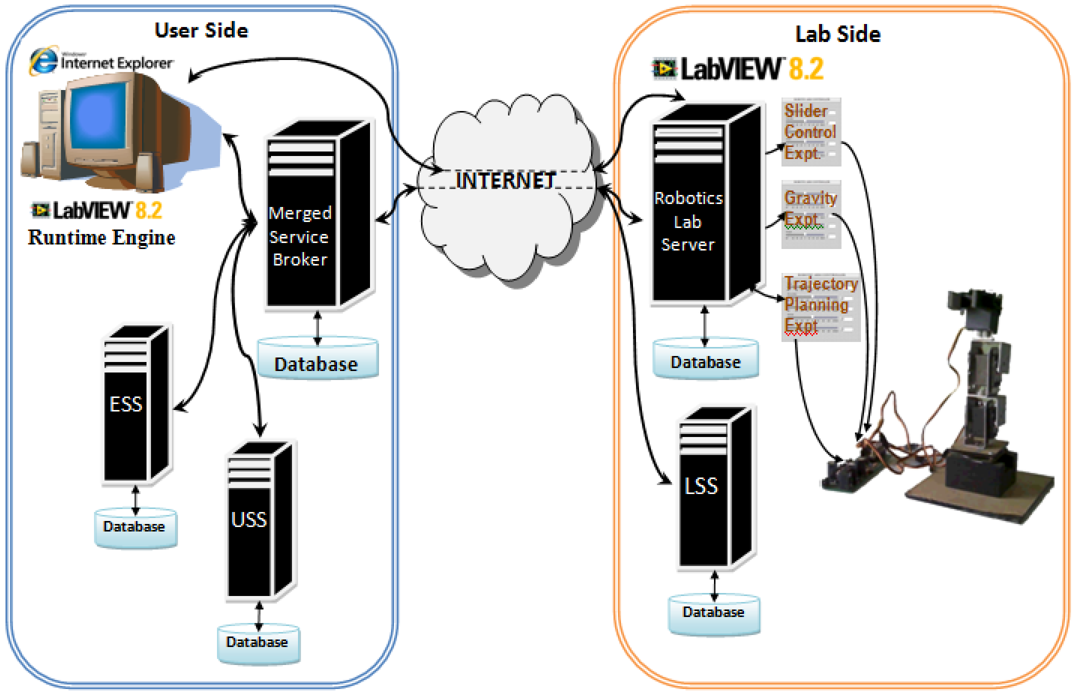


Figure 2: Topology of the Interactive iLab Architecture [9].

The ESS is used to store experiment results and details. The ISB, like the SB of the batched architecture, authenticates students and determines the level of access of the students.

The Client application can be implemented in any of several technologies e.g. as a java applet, an ASP.NET application or a LabVIEW application [5]. The use of LabVIEW is particularly attractive because this can reduce the time-to-deployment of the lab.

While interactive experiments do not use bandwidth as efficiently as batched labs and in fact, in most cases need much more bandwidth, they have the advantage of giving a better lab experience. Since experiments are done in scheduled sessions, the student feels a lot more like he is in a physical laboratory, than when performing a batched experiment. A second case for the use of interactive labs is the fact that some kinds of experiments can only be implemented as interactive experiments and not as batched ones. Such experiments include those which require the student to monitor the live response of the experiment setup to his specifications and then provide further specifications, for example, the control of a robotic arm.

## iLabs Developed in OAU

### *The Op-Amp iLab (OpLab)[6]*

The circuit under test for this laboratory is based on the Dozen-Impedance operational amplifier configuration (Figure 3) as reported by Kehinde [10]. The dozen impedance configuration is an operational amplifier circuit with a dozen impedances connected to it through switches in such a way that various basic operational amplifier circuits are implemented. For example, by closing switches $s_2$, $s_3$, $s_{12}$ and $s_{15}$, and substituting appropriate capacitors for impedances $Z_2$ and $Z_3$, the circuit becomes an Integrator or a Differentiator.

An LM 324N, a low power quad operational amplifier was used in implementing the Op-Amp iLab Dozen Impedance circuit. The switches were implemented using a multimode switch matrix developed around a PIC18F452 microcontroller and six MAX4664 FET

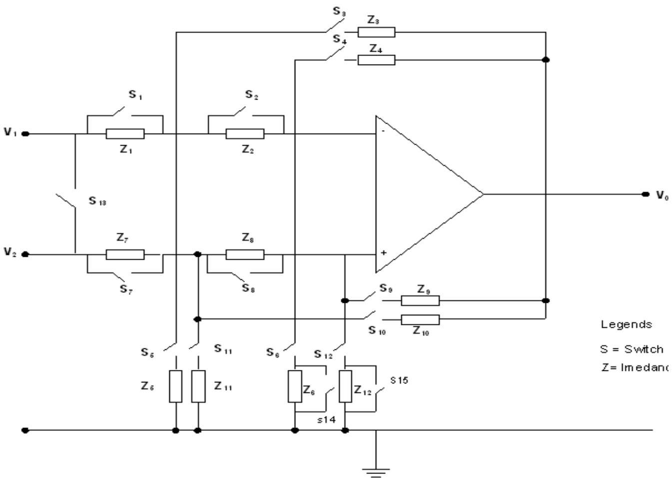


Figure 3: The dozen impedance Op-Amp Configuration.

switches. The switch matrix was connected to the RS232 port of the Server through a MAX232 level translator.

The circuit under test was mounted on the prototyping board of a National Instrument (NI) Educational laboratory Virtual Instruments Suite (ELVIS). NI ELVIS (Figure 4) is an instrumentations platform that integrates a set of measuring instruments with a signal generator and a power supply. Interfacing with a computer was achieved through an NI Data Acquisition (DAQ) card (NI ELVIS II needs no DAQ card, but connects directly to the USB port of a computer). The advantage of using ELVIS is that it presents all the instrumentation and measurement needs for a circuit under test in one single package that can be controlled programmatically from a personal computer [6].

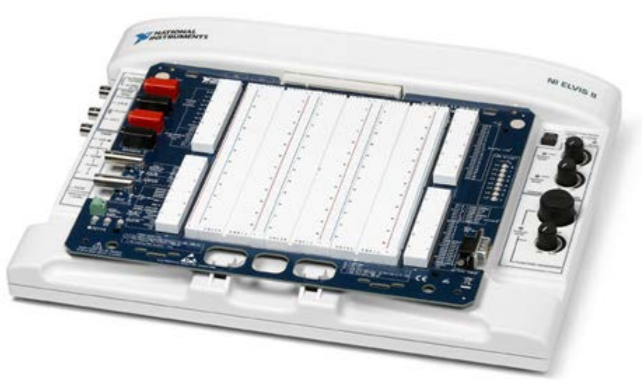

Figure 4: NI ELVIS II.

In the OpLab, students are required to connect the op-amp in one of the available configurations: Inverting Amplifier, Non-Inverting amplifier, Differentiator, Summer, Integrator and Unity Gain-Amplifier.

Students use this lab by configuring connectible nodes (opening and closing nodes in a circuit diagram) on the graphical interface of the client. The GUI was developed using C#. The user's interaction with the C# application API calls which are used to close and open the specified switches in the switch matrix. The resultant Op-Amp circuit is dependent on the nodes opened and closed by the student. Figure 5 shows the OpLab interface with the op-amp connected as an inverting summer, where the same input signals are applied to the two 39k resistors. Figure 6 shows the plots of the input and output signals for this experiment. The output is the inversion of the sum of the two input signals.

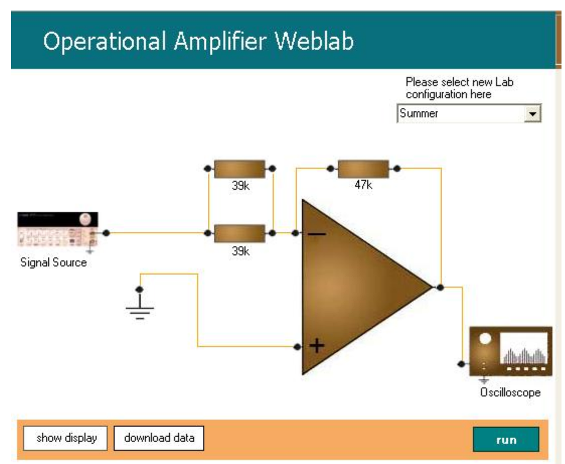


Figure 5: OpLab performing a summing experiment.

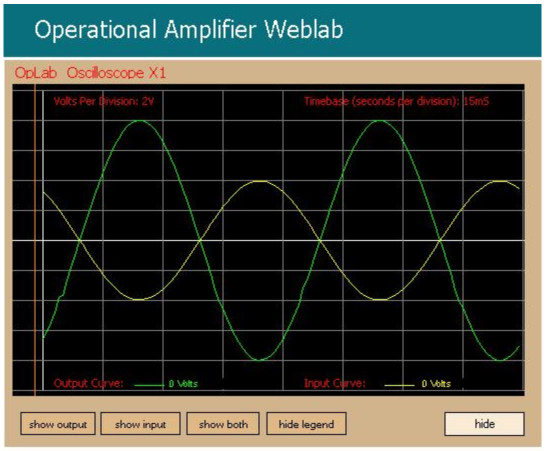


Figure 6: Result of summing experiment.

### *The Logic Design iLab (ADLab)[7]*

The Logic Design iLab, initially called the Advanced Digital iLab (ADLab) is a highly flexible lab designed to investigate the characteristics of digital logic. It allows students to synthesize digital systems on a Field Programmable Gate Array (FPGA) with VHDL, a hardware description language. The experiment setup is built around an Altera DE1 Development Board (Figure 7) which uses a Cyclone II FPGA. The backend system is built around the FPGA, and also contains web services, the experiment execution engine, QUARTUS software, and data acquisition (DAQ) software. The client application for this lab was developed using Java. The choice of Java was informed by the fact that the Java Virtual Machine allows Java code to have a level of platform independence that no other popular language has. Figure 8 shows architecture of the ADLab.

For experiments, students are required to design a digital device using VHDL and send this design to the lab for synthesis on the board. The user makes the VHDL description of the device and then specifies a set of test signals to be sent into the designed device. On reception of the student's specifications, the Quartus software parses it for errors and if no errors are found, synthesizes the design on the Cyclone II FPGA. The specified test signals are now fed into the FPGA and the measurements are taken from the output pins of the FPGA. The FPGA response is returned to the student.

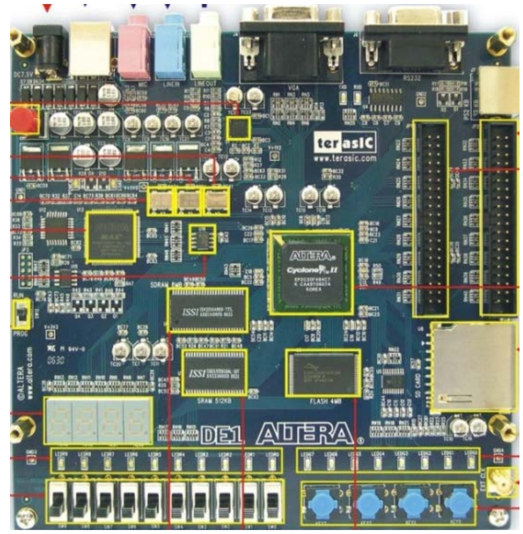

Figure 7: Altera DE1 Development Board.

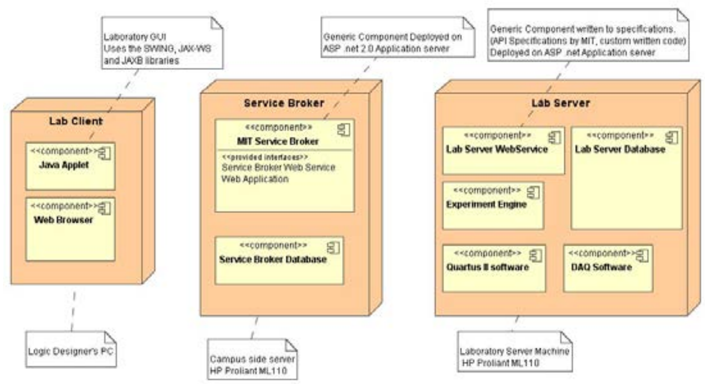


Figure 8: Architecture of the ADLab.

A screen shot of the ADLab client signals are shown in figure 9.

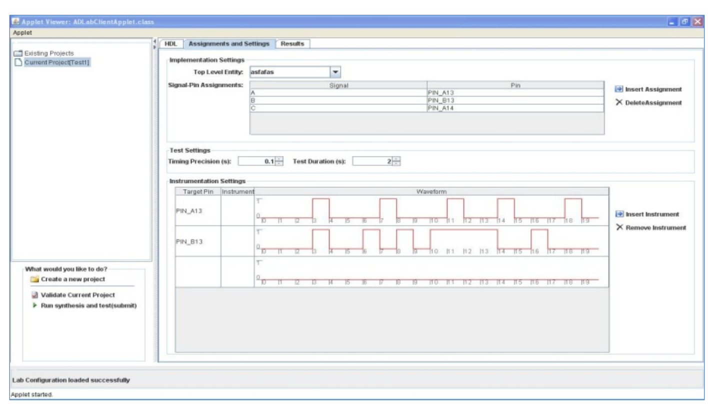

Figure 9: ADLab Client signals.

***Robotic Arm iLab [9]***

The OAU robotic arm iLab or robotics iLab can be used to perform three experiments: Position Control Experiment, Gravity Experiment and Trajectory Planning Experiment. The robotic arm in use in this lab is the RA-01 (Figure 10) robotic arm made by Images SI, New York. It has five degrees of freedom, four rotary joints (waist, shoulder, elbow and wrist), one prismatic joint (gripper joint).

Figure 10: The RA-01 Robotic Arm.

The position control experiment is targeted at people who are new to the concept of robotics. It literally just grants the students control over the individual degrees of freedom of the robotic arm. The angular positions of the links of the four rotary joints of the robotic arm are specified using four sliders, one for each joint. The width of the yawn of the gripper of the robotic arm is also controlled by a slider. Hence, the students control the position of the robotic arm via sliders.

The gravity experiment allows students to investigate the effect of gravity on the motion of the robotic arm. Students vary the effect of gravity by varying the width of position-specifying pulses being sent to the robotic arm.

The trajectory planning experiment requires the students to compute the angular positions which the links of the robotic arm should assume in order to move the gripper of the robotic arm from one point, through a path, to another point. This is done by computing the inverse kinematics of the robotic arm having been given the forward kinematics.

LabVIEW was used to create the client applications for each of these experiments. The clients for the position control experiment and the trajectory planning experiments are shown in Figures 11 and 12 below.

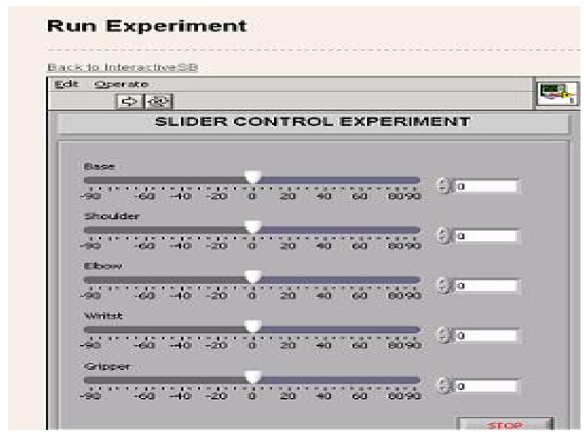


Figure 11: Clients for position control planning experiments.

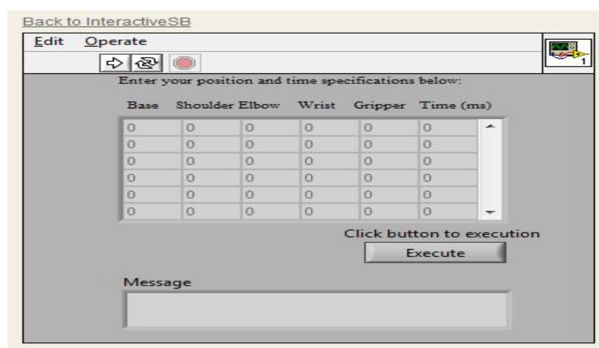


Figure 12: Clients for position trajectory planning experiments.

## The OAU Experience

This section will present the OAU experience in relation to the benefits of online laboratories over traditional laboratories. From OAU's perspective, the benefits of an online laboratory over a traditional laboratory are [11, 13]:

i. It presents users with the opportunity of performing experiments with laboratory apparatus which are not readily available in such users' reachable environment. Particularly in the African setting where funding of higher institutions is generally limited, the sharing of laboratories over the internet can enable students perform experiments which they otherwise would not have been able to due to the unavailability of the laboratory equipment at the universities.
ii. It creates and fosters the possibility of collaboration between educational institutions, thereby enabling a more comprehensive learning experience for students. Institution collaboration can occur in the development of the online laboratories or in the supply of different laboratories to an online laboratory pool, pooling together the strengths of each institution.
iii. It creates the possibility of having students from different institutions at different locations operating in distributed teams, fostering inter-institutional student collaboration.
iv. It presents the unique advantage of being able to run an experiment for demonstration during a lecture without the obvious inconveniences and sometimes impossibility of moving heavy equipment.
v. It presents great savings by reducing laboratory equipment redundancy in the learning environment. Placing laboratories online makes the sharing of laboratory equipment among educational institutions almost trivial.
vi. It provides a wider range of students with access to the laboratory experiment.
vii. Online labs increase the possibility of being able to perform experiments. With local laboratories, for a lab session to be possible, there must be a coincidence of the availability of laboratory equipment in the local environment, teaching assistants or lab instructors, the student and time to perform the experiments. With online labs, firstly, laboratory equipment does not have to be available in the local environment – geographical displacement of the lab equipment is not an issue. Software serves as the teaching assistant or lab instructor and hence, lab instruction is always available for the lab session. The only common bottleneck is time and with online labs, this constraint is relaxed as the lab can be made available to users 24 hours a day as no physical supervision is needed. The only other bottleneck for online labs is the availability of internet connectivity and adequate bandwidth. This limitation is rapidly dwindling as internet access and reliability is rapidly increasing.

## *Inter-University Collaboration*

### Knowledge Transfer

In the research to develop remote labs, OAU has enjoyed collaboration with a number of universities. OAU's collaboration with Massachusetts Institute of Technology (MIT) dates back to 2004 when Prof. del Alamo visited OAU. Since then, in the last five years, members of staff from both universities have exchanged visits to enhance the development of iLabs at OAU. During this period, two Masters' students and one undergraduate student have visited MIT from OAU to enhance their research work in the development of iLabs. Indeed, the robotic arm iLab client application was developed during the visit of one of the Masters' student to MIT.

At present, OAU is fostering collaboration with other universities in Nigeria to aid them develop their own iLabs, and take advantage of the laboratories already developed at OAU.

### Research Funding / Support

OAU has received support in terms of funding and equipment through the MIT-OAU collaboration on the development of iLabs. The NI ELVIS used in the development of the OpLab and LabVIEW, used in this paper for the robotic arm iLab client application, were obtained from National Instruments Inc. through this MIT-OAU iLab collaboration. Funding of OAU's iLab programme was received from the Carnegie Corporation, U.S.A. via the MIT-OAU collaboration.

### Lab Equipment Unavailability vs Redundancy

One of the benefits of remote labs is that they can be used in cases where requisite laboratory equipment is unavailable in a local institution. For instance, in cases where one institution cannot afford a particular equipment, as is the case for some requisite equipment in a number of African Universities, if this equipment is available in another university, no matter how geographically separated, the equipment can be set up as a remote lab so that staff and students from both universities can perform experiments on the equipment.

The argument above also means that remote labs can be used to reduce equipment redundancy in educational institutions. By getting universities to share experiment setups, each university ends up with relatively more funds to buy lab equipment not currently available in the iLab consortium.

One of the first iLabs to be used at OAU was MIT's Microelectronics iLab. Students from OAU were granted access to MIT's microelectronics iLab to perform microelectronics experiments on their experiment setup. In the same vein, OAU is fostering collaboration with some select Nigerian Universities to make its already developed iLabs available to their students.

### *Enhanced Lab Experience / Self-Learning*

### Hand-On Experience

Most of the laboratories at the undergraduate level see several students thronged round a work bench to perform experiments. Typically, in such groups of students, only one or two fully grasp the concepts being taught by the experiment and hence participate in the experiments. Most of the other students in the group never really perform the experiments, but they copy the results from the others. With remote labs, each student can be made to perform the experiments.

Since students log on the service broker to perform experiments, the course instructors at OAU are able to check to ensure that each student submitting a lab report actually logged on to perform the experiments. A second method used was to run searches through the submitted lab reports, searching for similar words. Reports found to have similar words were then scrutinized by the course instructor to see if the students copied the results from each other. Other approaches to ensuring that each student gets the hands-on experience are being explored.

On the whole, from the response students provided to questionnaires given to them after performing the labs, most students were glad to be able to perform the experiments for themselves on physical equipment (remote or local) [6,7]. Hence, most students were glad for the opportunity to perform the labs using our iLabs. The robotics iLab has particularly attracted attention because, though we do not have a robotics credit-awarding course, the field of robotics is rapidly gaining ground in OAU. The robotics iLab has provided students with the opportunity to have hands-on experience with a robotic arm without any fears of wrecking havoc.

### Lab Interface

Students using the OpLab sometimes complained that the lab felt like a simulation. Conversely, with the incorporation of the webcam into the ADLab and the Robotic arm iLab, students commented that they enjoyed a richer and more realistic lab experience. This has opened up a research aspect at OAU on how to enhance iLabs such that the student gets a good experience at minimal bandwidth cost.

One aspect of this work was reported in 2008 [14], in which a set of interfaces termed realistic-looking interfaces (RLI) was developed. RLI emphasize realism and fidelity to back-end hardware appearance, and eschew representation of devices-under-test with schematics or symbols. The argument that led to the development of RLI was that students instinctively associate remote labs that use schematics-based metaphors with simulations, but are more likely to think of the underlying hardware if the interface depicts the actual appearance and physical characteristics of the backend hardware. RLI were developed for the OpLab and a new Strength of Materials lab. Since RLI require a tight integration of data in audio, video as well as text form, they are best implemented using rich internet application (RIA) platforms. The RLI for the OpLab and the Strength of Materials lab were developed with Adobe Flex and Java 3D respectively. Students' response to the new interface metaphor was overwhelmingly positive and they generally ascribed more gains from labs employing the new interface than they did for the same labs with traditional interfaces.

## *Curriculum Enhancement*

### Curriculum Delivery Enhancement

One of the benefits which iLabs have brought into OAU is the enhancement of its curriculum. An advantage of remote labs is that they make it possible and trivial to run live experiments during a lecture session thereby enhancing curriculum delivery to the students. While OAU has not been able to take full advantage of this benefit of remote labs, in courses which iLabs have been developed for, the lecturer can regulate the performance of experiments related to his course.

The OpLab has six experiments which can be performed in it, different labs for different aspects of the “Operational Amplifiers and Active Networks” course. With the OpLab, the lecturer of the course has been able to regulate when students perform which experiments and hence get the students to practice concepts which are freshly taught in class. Prior to the existence of the OpLab, due to student population, students had to be scheduled for lab sessions “haphazardly” such that while some students performed the experiments long after the concepts were taught in class, others had to perform the experiments before encountering the concepts in class. With the OpLab, however, each student is made to perform the required experiment on a particular concept freshly taught in class and given a space of a couple of days to submit his report.

Report from students on performing the experiments in the OpLab showed that their understanding of the Op-amp concepts was increased by the experiments. This was further enhanced by the fact that each student was able to perform the experiments individually as opposed to a typical traditional lab session where up to fifteen students would crowd round a workbench such that only one student really does the experiment while the fourteen others copy the results often with no inkling of how to make the connections themselves.

### Curriculum Expansion

Remote labs make it easier to expand the curriculum by making more experiments available to students. The development of the ADLab and the Robotic Arm iLab expanded the curriculum of the “Pulse and Digital Techniques” and “Dynamic System Simulation” courses of the department of Electronic and Electrical Engineering at OAU. “Pulse and Digital Techniques” was expanded to include the learning of VHDL and the use of FPGAs. “Dynamic System Simulation” has been expanded and will, in the current semester, also handle the modelling and simulation of a robotic arm.

Also, with the ubiquity of these two labs (ADLab and Robotic Arm iLab), a number of students not registered for these courses have approached these course lecturers requesting permission to perform experiments in these labs.

Hence, the knowledge base of students have been expanded and we only wait to see the results this expansion will yield!

### *iLabs is a Research Area*

The development of iLabs is a research area in itself. At OAU, one Masters thesis and about three undergraduate reports have been completed in the development of iLabs. At present, one PhD thesis and one Masters thesis are nearing completion in the development of iLabs.

### *Student Intuition*

Security is a necessary integral part of all remote labs – security of lab equipment setup. Since there is no physical lab instructor present when students are performing the remote labs, there is a need for the remote lab system itself to be able to be able to supervise user input to ensure that it does not exceed pre-defined limits. Hence, once a student is using a well-designed remote lab, the student need not fear damaging the lab equipment. Hence, he is free to use his intuition to try out specifications not stipulated in the lab manuals. Hence, student intuition is promoted.

In OAU, two of our developed labs, the ADLab and the robotics iLab, are particularly supportive of student intuition. While for experiments in these two labs, students are given specific tasks to carry out, they are not restricted to these tasks alone in the lab. In the ADLab, the student, apart from synthesizing the digital system specified by the instructor, the students are free to design and synthesize any system which they can conceive. The only limit to their design is the capacity of the Cyclone II FPGA and the Altera DE1 development board. In the robotics iLab, the students, since the have control over the robotic arm, are free to experiment with how to programme the robotic arm to perform specific tasks – whatever task they can conceive which relates to “picking and placing” or trajectory planning.

## Constraints and Challenges

While iLabs have been very useful in OAU, they are obviously not a magic bullet that will solve all problems. A number of constraints and challenges have been noted.

### *Physical Hands-on Experience*

Remote labs have the major short-coming of not being able to provide the students with physical hands-on experience. Hence, rlabs deny students the opportunity to develop sensory awareness (mostly haptic and olfactory) in experiments. A lot of research is going on, the world over, into how to, with minimal cost, deliver the full laboratory experience to students over the internet.

In our experience, this singular point has been the main argument which several lecturers and institutions have put forward against the infusion of iLabs into their curricula and institutions, when approached by our team. The view of the OAU iLab team is that while remote labs cannot completely replace traditional labs with the current technology, “half bread is better than none!” This is congruent with the conclusion of Aktan that remote laboratories are the “Second Best to Being There (SBBT)” [12].

### *Reliance on Network Uptime and Bandwidth*

Students access iLab remote systems-under-test through computer networks and a downtime on any segment of the link between student and hardware means the student will not be able to carry out his experiment. This fact is especially problematic in Nigeria, which has a very well-known problem of power generation and supply. Apart from outright network downtime occasioned by power problems, bandwidth constraints in most parts of Nigeria also sometimes adversely affect students’ experiences.

## Conclusion

From our experience with the development of iLabs, the following conclusions can be reached: iLabs can be used to enhance student intuition and perform very important roles. They enhance curricula as well as curriculum delivery, and present students with possibility of having "hands-on" experience with equipment which they would otherwise have had no access to. However, it is important to note that as yet, iLabs cannot replace traditional laboratories. iLabs also serve as a very viable basis for inter-university collaborations and iLab development is very much an on-going research area.

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