An Overview of System Architectures for Remote Laboratories

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***Abstract*—Remote Access Laboratories have been successfully installed around the world enabling students to practice practical skills and develop their knowledge through experimentation. Remote laboratories have the advantage of being accessible from anywhere anytime allowing users more flexibility and mobility. Typically installations are designed to resolve issues of access or utilization. Clear pedagogical design is now seen as a critical development in the instigation of new experiments, and access systems. This paper examines existing system designs, using a Program Logic analysis to identify key inputs, outputs, and impacts for the creation of systems. It aims to identify commonalities, or differentiation with respect to the original goals. Through this analysis it was identified that many RAL systems implement direct mimic user interface design focusing on individual access to a kinesthetic learning experience. Learning design is also typically implemented by the system and experiment designers, potentially reducing the impact of the system or activity usability.**

Keywords— remote laboratories; e-learning; remote access laboratories networking; web technologies

I. INTRODUCTION

In science and engineering education, the combination of theoretical knowledge along with practical experience linking the concepts is essential, and is a requirement of Engineers Australia (EA). Commonly the theoretical delivery consists of lectures and exercises supplemented by textbooks and lecture notes. Practical experience is then typically gained through interaction with real technical instruments and devices that exhibit real phenomenon as described in the theory. Remote Access Laboratories (RAL) or Remote Laboratories (RL) are online systems where users control and observe the characteristics and operations of a piece of equipment from a remote location via the internet, e.g. [1-5]. These RLs have the capability to support or replace on-site laboratories; provide improved access and learning at lower cost; and encourage sharing of expensive resources amongst parties. A number of collaborative projects have integrated experiments under a common infrastructure. Aims of these efforts typically include simple access by students and support of collaboration among students [6-7]. Research has been undertaken to integrate RAL experiments into undergraduate courses [8-10]. In addition, this technology has also been successfully implemented and used for laboratory education. RLs can provide access to resources which are otherwise inaccessible to users. Typically all that is required is a web browser and an internet connection to enable this rich educational and learning experience. Traditionally remote laboratories have been deployed by institutions for their own student cohorts or community members associated with the university. A survey conducted in 2010, suggested that 'Virtual & Remote Labs' are the best options to enhance engineering education [4].

This paper focuses on the research question as to whether specific architecture offer advantages over other systems, and attempts to develop a model of what key components comprise a "good" RAL system. In this work, the common constituents of several leading Remote Laboratory Management Systems (RLMS) are compiled and studied. It is observed that the various components are implemented in different ways as discussed later, but still retain common properties. The general characteristics of remote laboratories are compared to establish the common standards being followed for creating RALs, and how their designers use them for teaching. This is stated as a reason for a relatively slow adoption of RAL as a regular tool, especially within K12 education.

In section 2 the expected standards for remote laboratories are expressed with respect ABET followed by a program logic model to explain the origin and development of remote laboratory architectures in Section 3. In section 4, the common characteristics are formulated followed by detailed examination of different RALs based on technical criteria and an evaluation of features are presented in section 5 and 6.

II. RESEARCH FRAMEWORK

Laboratory and practical activities form an integral part of Engineering Education. At an ABET Colloquy [11], a set of thirteen common learning outcomes for engineering laboratory activities were identified. Traditionally practice classes are taught face-to-face; however, Remote Access Laboratories have been widely discussed as potential alternatives for online delivery. Drivers to develop remote laboratories differ and include the ability to share hardware between physical locations within and between and institutions e.g. remotely controlled robots [12] and control laboratories [13], economic benefits [14] and access for distance education students [15]. RAL literature largely focuses on technical system implementation details; questions regarding learning outcomes and pedagogy are often not addressed. Another common deficiency with laboratory work in science and engineering curricular is that objectives for practical activities are not explicitly addressed [11]. This makes it difficult to judge the educational effectiveness of RAL activities. In particular since "the pedagogical effectiveness of any educational activity is judged by whether or not the intended learning outcomes are achieved" [16]. As this paper focuses on the system design, it addresses this question by considering the factors that lead to the creation of a RAL, as well as the sub components that make up the final system with respect to both technical requirements, as well as educational and pedagogy considerations.

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III. METHODOLOGY

To evaluate and compare different RAL systems and establish whether individual approaches have major advantages over others, a Program Logic method [17] is used. This method maps inputs, activities, outputs, outcomes and impacts. As this paper addresses the overall system design, the evaluation is limited only to aspects that are relevant in this context. Fig. 1 summarizes the program logic used for a generic RAL system.

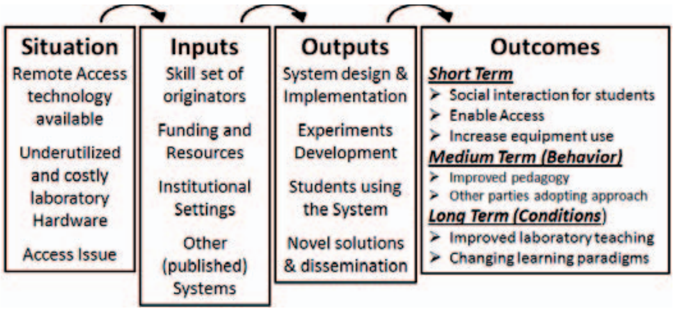

Fig 1. Program Logic.

The situation is depicted on the left-hand side and includes the technical advances that have been possible with the developments in computing and communication, i.e. the Internet. This also includes generally underutilized laboratory spaces and student access to practical experiments. In the context of distance education, for example, this issue is dominant. The next box depicts the inputs. Most RAL systems have originated from academics with a keen interest in technology. Additionally, funding, institutional support and other resources play a vital role. Another consideration is that of isolated development, or development based on other published system designs. Outputs include the actually developed RAL system that solve the access problem and the experiment or 'rig' design. Students using the systems and dissemination of novel results are also important outputs. The impact of these activities is arrived at by improved access for students (temporal and geographical) and collaborative opportunities; improved pedagogies and wider use; as well as changes to learning and teaching paradigms. To complete the methodology, the following aspects of these systems where evaluated: Initial Problem, Pedagogy, Web Interface Design, Innovative Features, Users, Scheduling, Programming Languages, impact and major academic fields.

IV. REMOTE LABORATORY – BASIC COMPONENTS

Within a RAL system there are traditionally two nodes, the server and the client (see Fig. 2). The users' side consists of the students engaging and learning from use of the experiment, with the server side providing the experiment 'rig', as well as the experiment designers responsible for designing, creating and maintaining the experiment designed to allow experiential learning of concepts and learning materials. RLMS are responsible for arbitrated interaction between all components and interfaces in the system. Typically RLMSs have certain common components:

1) *Scheduling*: This aspect is one of the most important and well-investigated aspects of remote laboratories. Typically the scheduling aspect highlights the difference between the on-site and the remote laboratory. Because online users are unaware of each other's activities within a system, interactions with the experiment hardware needs to be coordinated. RLMSs have addressed this concept in different ways [18]. There are however two fundamental strategies used; queuing; and time-slotted booking [19]. In some RAL systems where only brief interactions between users and rigs are required, a reservation mechanism is used where users are presented with links to the experiment on a first-come-first-serve basis.

2) *Rig operations*: An experimental rig typically consists of a group of devices or instruments under local or remote computer control. The RLMS then makes experiment requests of this system, both sending commands, and then receiving collected data. This involves setting up a connection between these subsystems, and following a particular format for data handshake exchange.

3) *Transport layer*: This is the communication link layer between the User Interface (UI) and the back-end instrumentation server. There are two ways to implement this layer. The first utilizes a web services (WS) method (i.e. HTTP), which recalls a URL indicating the location of the instrument with users parameters. The second method uses a desktop or screen sharing method (RDP or some variant) in which, the entire server screen is copied to the users side periodically. The WS method allows implementing complex time scheduling mechanisms for the experiment, and allows for flexibility in UI design to hide the instrumentation control software. Alternatively, native software can be used directly when implementing the desktop sharing method, which is useful for out-of-the box experimental configurations.

4) *Multimedia tools/data about experiments*: Any information system for e-learning must provide documentation regarding the context of the experiment. Many RLMS provide tools to view or analyze data obtained back from an experiment. Often live video feedback is necessitated to observe in real-time the feedback within the experiment. For certain types of experiment this visual feedback may be an important or critical means of obtaining experimental data to support mechanical and control theory laboratories.

5) *Experiment user interface*: Users interact with the experiment typically through either a web browser, or a browser based thin-client, or in some cases a standalone application [20]. These UI(s) allow the users to observe, interact and control the test equipment, as well as acquire the data or results.

6) *Accepting and processing user request*: Experiments used for undergraduate and graduate laboratories should have limited controls on the types of inputs that can be accepted. As such the system needs to prevent improper inputs from damaging the equipment such as an electrical short circuit [21] or high excessive voltage on components. Hence the system should present both corrective and limiting factors within the UI, and/or within the experiment. This has been referred to as a virtual fence [22].

7) *Storing and maintaining user details*: This is a fundamental block of any information system, where critical information regarding the users is stored in central databases. User details include courses, user groups and experiments they are required or eligible to operate.

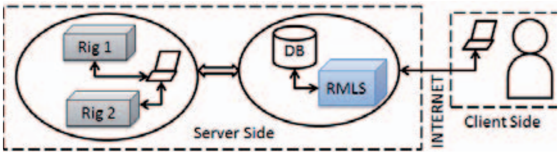

Fig. 2 Typical RLMS System Architecture

V. Study Of Different RAL Systems

Some of the largest and most widely used RLMSs are chosen for comparison because these have been developed and used for several years. These include:

- iLab is a flexible software infrastructure for the implementation of internet accessible labs at MIT, USA since the late 1990s [1, 10] later adopted and some of its features extended by others [23] resulting in further research and implementation of experiments. It uses LabVIEW as the main programming language to operate the instruments through its web servers.
- The University of Technology Sydney (UTS) developed an RLMS for use from 2000 to 2005, later known as SAHARA and adopted as part of the much broader Labshare initiative [6]. It is the result of collaboration between several Australian universities being the University of South Australia, University of Technology Sydney, Curtin University of Technology Perth, Queensland University of Technology, Brisbane and Royal Melbourne Institute of Technology, Melbourne. The SAHARA system framework provides a generic toolset for configuring and enabling a heterogeneous remote laboratory of physical instruments.
- Virtual Instrument Systems in Reality (VISIR) started in 2006 at the Blekinge Institute of Technology, Sweden. This system provided an online workbench operating as an open laboratory platform [21]. Unlike the previously two, it does not come with prepared remote experiments already setup at the server side, but offers a software simulation environment toolkit, released under a GNU GPL license, to allow other users to implement online laboratories where experiments are performed within preset limits set by staff, just as in on-site laboratory.

A. *System architecture*

The iLab has a three layered architecture called the iLab Shared Architecture (ISA). Users connect with a service broker server, which in turn makes a connection with the actual laboratory server. The system architecture is heavily dependent on web services [1]. iLab has also been used to implement extensions such as iLab-MIT-Africa [24] in African nations and some universities in Australia. Experiments in iLab have been categorized into three different delivery methods: batched, interactive and sensor. iLab is based on the Microsoft platforms including Visual C#, .NET framework tools and Microsoft SQL Server. This makes the system very platform dependent, consequently it is difficult to implement on open source platforms. Recent attempts are being made to re-implement the ISA in Java in an attempt to make it platform independent [25]. SAHARA originally followed a client-server architecture, where all experiments were hosted at the UTS laboratories, and accessed upon request by remote users. In this design, the lists of experiments are stored by the central server, which is also responsible for other operational aspects including running the RL, scheduling, and operating the rig. Recent developments in SAHARA have moved towards grid architecture, but mostly within partner institutions. VISIR implementations also follow client server architecture, where all the experiment lists are stored in centralized databases along with user details, and connection to the same server is used for booking and operating the experiment. Both iLab and VISIR use LabVIEW as the main platform and language to write programs to operate instruments.

B. *Experiment scheduling*

iLab follows a queuing method for scheduling experiments with users. All requests are placed in a queue and processed successively one after another. Users of VISIR follow a time-slot booking method by assigning a particular time period in the future to a particular student [8]. Only the student allocated that time-slot can control the instruments and measure data. The SAHARA package supports queuing, time slot booking or a hybrid combination of both these methods [6]. Teachers can also make requests to the laboratory manager for a rig, upon which it is shared with the interested group.

C. *Deploying new experiments*

In all cases new experiments are chosen by the administrators based on the university curriculum and educational needs according to the subjects being taught. The instruments used are typically of high cost featuring complex functions. Due to the nature of the experiments, these systems have to be developed within the laboratories of participating universities. The experiment configurations are generally composed of several experimental apparatus operated by a high level language, and typically involve a PC computer based controller. The user interface for the remote laboratory is also typically created by the laboratory staff. The scheduling aspect is easy to implement for instance as in the SAHARA software. These features allow developers to implement their own laboratory management systems. VISIR, which provides workbench environment and set of experiments, is flexible but still limited to the number of experiments that can be performed with the given restricted component set [26]. In this instance there is no scope of deploying any new module extensions, except for where VISIR developers extend the features and components of the hardware.

D. *Nature of experiments*

Within iLab the experiments are varied in nature and maintained by different laboratories at MIT with different experiment focus. The micro-electronics laboratory for instance is the most used experiment. In addition to this, there are other laboratories for control theory, circuits' laboratory, micro-electronics and physics. All laboratories are built with a key focus on the required laboratory experience for undergraduate and graduate courses. For Labshare, the experiments are also from varied fields such as physics and electronics. VISIR restricted for use with the analog electronics basics experiments [27]. The UI for VISIR features considerable flexibility and intelligence. The users can assemble and measure currents, voltage and other properties of serial and parallel circuits. The environment can detect and immediately inform users making incorrect connections such as short circuits. This increases the

TABLE I. COMPARISON BETWEEN LABS

	Netlab (UniSA)	*LiLa*	*iLab, MIT, USA*	*VISIR, Sweden*	*Labshare, Australia*	*WebLab , Duesto*
Initial Problem	Accessibility	Resource Sharing	Accessibility	Accessibility, User Experience	Resource Sharing	Accessibility
Pedagogy	Investigated Implemented		Investigated	Investigated	Investigated	-
Web Interface Design	Similar to classroom	-	Mimic Interface & LabVIEW interface	Similar to classroom	LabVIEW interface Mimic Interface	Mimic Interface
Notable System Features	Co-operative Activities	Consortium, LiLa Learning Objects	iLab Shared Architecture (ISA) & service broker	Flexible electronics circuit hardware	Collaboration	3D Interaction
Users	Undergraduate	Undergraduate	Undergraduate	Undergraduate	Undergraduate	Undergraduate
Scheduling	Time-Booking	Time Booking (rig booking)	Queuing (batched expts.) & Time-Booking (interactive expts.)	Time-Reservation	Time- Booking Queuing Hybrid	Time-Reservation (with priority Queuing)
Programming Language(s) - Rigs	JAVA	None	LabVIEW	LabVIEW	LabVIEW	-
Programming Language(s) - UI	JAVA	HTML	JAVA	Flash	LabVIEW Interface	HTML, Flash
Major Academic Fields	Electrical Circuits	-	Control theory, Circuits laboratory, micro-electronics and physics	Analogue electronics	physics, electronics, electrical	Physics, Electronics (FPGA)
Impact	Initiated Co-operative Experiments	Used by others as a booking system	Used in Africa and Australia	Collaboration with others	Used by school students	Collaboration with others

students understanding about what can go wrong while designing a circuit. Although VISIR provides more definite sets of experiments, it is restricted to core electrical and electronics education for undergraduate students [28]. VISIR has been used by several universities such as Carinthia Technical Institute Austria, UNED Madrid Spain, Univ. of Duesto Bilbao Spain and ISEP for their undergraduate curriculum.

E. Some other notable RLMS with additional features

Univ. of Duesto, Bilbao Spain developed the WebLab-Deusto remote laboratories [3-4] in the early 2000s. This system uses the client-server mechanism, utilizing mostly time reservation with priority queuing based scheduling [19], although the nature of scheduling can change if connecting to other systems. Within this particular system, there is a wide variety of experiments ranging from basics of physics to FPGA [29], although the main focus is on electronics and electrical experiments. But like all RLMSs, new experiments are designed by laboratory experts based on educational needs of their undergraduate students. The most notable features of WebLab are - Integration with other RLMSs such as VISIR [30] to use their experiments and a 3D user interface in second-life called the 'SecondLab' [31]. SecondLab merges all the RAL components and allows students to program a micro-bot from Second Life with visual feedback. However the experiments portal is highly dependent on the type of experiment being implemented.

In 2011, the project 'LiLa' (Library of Labs) was started as a collaborative venture between several RAL installations throughout Europe. Many virtual and remote experiments were shared by partner institutions through a Learning Management Systems (LMS) and the 'LiLa Internet Portal'. The learning aspects of LiLa were managed using SCORM, a learning object creation and management tool [7]. This project amalgamated several laboratories using diversified technologies, and acts as an intermediary system to find, book and pass experiment request to the actual laboratory servers. Teachers were then able to locate and assign experiments to their students. Actual costs of the laboratories however were still borne by the participating universities. LiLa utilized simple client server architecture and operated in a similar manner to the shared broker architecture of iLabs. Some of the other notable RAL systems across the globe have been listed in Table 1 along with their respective features. All of these follow some variation of the client server architecture.

VI. EVALUATION OF THE DIFFERENT RLMS

To establish the difference between the systems the following criteria were examined:

A. Origin of the remote access laboratory

Most laboratories have their origins addressing problem of inaccessibility of equipment (i.e. more students and limited instruments) including iLab, Netlab (UniSA) and WebLab-Duesto. The UTS laboratories were developed to offer more expensive and hence higher performance instruments than the ones being used in the regular laboratories. Later Labshare and LiLa were initiated to share resources among different institutions in Australia and Europe. VISIR was initiated to provide knowledge of the difference between simulated data and real experimental data on a computer.

B. Innovations to increase the students learning

As with the original concepts of RAL, each system started by providing access to the instruments over the internet, i.e. that users be able to access the instruments from their computers. Later, several innovative steps were introduced that could be used to enhance the student learning such as:

1) 3D Environment: Several RAL systems have used 3D interactive and immersive environments to simulate the real world experience in the virtual world. The RemoteElectlab

(Porto) has preseted a case study for accessing a digital multi-meter through a 3D immersive environment [32]. iLab have created the TEALsim system to provide interactive physics experiments on magnetism [33]. REXLab has implemented a young's modulus experiment in a 3D virtual laboratory environment [34]. WebLab also introduced the most significant of these 3D systems, SecondLab, which is based on the SecondLife virtual world environment [31].

2) Co-operation between students in experiments: Operating experiments via the internet also allows for co-operation and collaboration between different students interacting, watching or lurking within the same experiment simultaneously. All of the 3D environments stated above already allow multiple users to access the experiment at a given time. In these instances, the users are represented by their avatars. Netlab was one of the earliest systems to implement interstudent collaboration [20]. Should it be desired, a multiuser interactive collaborative environment is required to allow concurrent users to have control over the entire experiment simultaneously.

3) Dynamic Components Assembly: VISIR created a relay based dynamic circuit assembly system to allow students to build and test circuits during sessions by using micro controllers through a computer server. The Netlab system also follows a similar approach to connect several instruments together dynamically to form the experiment.

In addition to the above, scheduling has been investigated as a specific problem in RAL by WebLab and Labshare [18].

C. *Replication of Classroom Experience*

Because the basic desire to create an online rendition of experiments was to provide laboratory resources to increase number of students, all of the laboratories implemented the mimic style web interface to the laboratory. For instance, Netlab and VISIR accurately replicate the actual instrument panels on the web pages [20]. However, with the increase in use of LabVIEW's front panel design, the interface has become more tightly integrated as in Labshare. For instance, a customized digital interface, containing only essential components of the experiments and not replicating a devices traditional interface, has been used for many experiments in iLab and WebLab (Duesto). A notable example is the 3D Virtual experiment where a 3D version is presented that shows the experiment action with additional simulated elements (the magnetic fields) otherwise not possible in real laboratories [33] as a form of augmented laboratory reality. These characteristics however vary from one experiment to another within a particular system.

D. *Pedagogy*

RALs are traditionally seen as replicas of on-site laboratories and typically expected to operate in a similar manner. As mentioned in [4], "It's probably a safe bet that few, if any, engineering programs implement remote labs for pedagogical reasons…" Remote labs usually do not carry any additional pedagogical values. However, the pedagogy of a RAL system itself has been investigated. Both iLab and Labshare developers have explored on the deciding factors on which laboratories and experiments can be converted to RAL [1, 35, 36]. NetLab and Labshare have conducted studies on the effects of RAL on students learning outcomes [37-38]. Netlab has also implemented a system where multiple students can work in co-operative manner to reproduce the actual laboratory experiences [37].

However, it is clear that while several developers have improved and worked on different aspects of the RALs such as user interface and experiment pedagogy, the core architecture has essentially remained the same. Some of the similarities may be summarized as follows:

1) The current trends for developing RALs allow only experienced and expert developers to create an experiment. The experiment variety is hence limited and concentrated on particular fields of higher education.

2) The instruments and devices used are mostly costly and complex to build and operate [39]. They use industrial standards such as GPIB, LXI [40] and PXI to connect the hardware to the computer servers. High performance software for engineering such as LabVIEW, VEE and MATLAB are also widely used to implement these experiment setups. Thus 'Rig Operation' remains a matter of high complexity in all RLMSs.

3) The laboratory management systems are predominantly client-server in nature. All users need to log into a web address and provide user credentials to authorize access, select an experiment before utilising it. Any grid technology implemented is essentially limited to the server side of the architecture. The experiment configuration is also centralized and maintained under high-end laboratory conditions. All laboratories are designed to be operated for long periods and available to students all the time.

4) There is very limited scope for collaboration among students in different geographic locations, and not typically available in RLMSs except for forums [6], although this issue has been given importance in some systems [20, 41-43]. There is also a trend to incorporate 3D user interfaces for collaborative learning purposes [32-34]. There have been multiple reports of 3D UI in various laboratories using different platforms, but it is not clear how many students have used these systems; the positive effects learning outcome have been reported [34].

5) The experiments are mostly concentrated on providing for engineering courses in undergraduate and graduate degrees. There appears to be little attention directed towards school level science education (STEM), which is rapidly becoming an important area for development using enquiry based learning methods.

CONCLUSIONS

Although RAL technologies have considerably improved in the past decade, thus far the focus has been on replicating the experience of on-site laboratories as accurately as possible within a remote web based environment to maintain an equivalent learning outcome. Developers or providers mostly operate with the goal of providing a web-based version of the laboratory exercises in their curriculum. This results in an online learning tool that aims to remove the time and space constraints. The pedagogical needs of the experiment are typically determined by the person in charge of the actual experimental lab. Any additional educator wishing to use the lab must adhere to the given set of data or existing constraints within the experiment. This has led to a large numbers of RALs with common standard characteristics. These standards are however complicated for individuals with little to no experience in networking or instrumentation, such as in schools. The internet and advanced web technology has reshaped and had a profound effect on peoples interacting and learning methods with features like social media allow users to interact at a personal level. For RLs to become more effective, they must increase their scope from a traditional interpretation of laboratory to something that better utilizes the internet and computer to increase the value of the learning. Through utilization of newer web technologies, it has the potential to provide much richer student engagement, collaboration, and support when remotely interacting with laboratories.

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