Delivering authentic experiences for engineering students and professionals through e-labs

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Abstract— **Use of leading industrial technology in 'remote experiments' and 'virtual laboratories' delivers authentic experiences to engineering students. Both types of learning resources can easily be shared between universities or industrial partners, leading to dramatic reductions in the costs associated with development, construction, operation and maintenance of traditional laboratory set-ups; however, each is characterised by inherent advantages and disadvantages. We compare and contrast remote experiments and virtual labs, using two case studies: 'Cambridge Weblab', a remote experiment built by the Computational Modeling (CoMo) Group at the University of Cambridge and 'SRM web-suite', a virtual lab developed by CMCL innovations. The Cambridge Weblab remote experiment uses a Siemens SIMATIC PS7 industrial interface to control a chemical reactor, yielding authentic experiences of industrial practices for students. A variety of pedagogical approaches employed by institutions using the Weblab are also discussed in this paper. The SRM web-suite uses an advanced engine design tool that simulates fuels, combustion and emissions in conventional and advanced internal combustion engines. The detailed simulations have been precisely tailored for training and educational settings. The web-suite labs provide students and engineering professionals with experience using the latest industry-standard technology, whilst supporting a wide range of educational goals e.g. undergraduate courses in combustion engines or chemical reaction engineering and advanced courses in futuristic fuels or powertrain engineering. We also assess the potential impact of these learning resources within the pan-European Library of Labs (LiLa) framework. Ultimately, we demonstrate that remote experiments and virtual laboratories are complementary, that there is significant potential for future integration of the two technologies, and that both can benefit from the latest industrial technologies.**

Keywords- Library of Labs (LiLa); remote experiments; virtual laboratories; chemical process control; advanced combustion engines

I. INTRODUCTION

A. *What are e-labs?*

This article compares three types of laboratory setups: conventional laboratories, remote experiments, and virtual laboratories. In a conventional laboratory, students are physically present in the laboratory, interacting directly with laboratory equipment and communicating face-to-face with classmates and instructors. In contrast, a remote experiment is performed on physical equipment housed in a laboratory, but is controlled by the student remotely, typically communicating with the laboratory equipment across the Internet. The software interface providing the controls of the remote experiment may be custom built [1, 2] or designed using a number of commercially available solutions [3, 4, 5, 6, 7]. Finally, virtual laboratories simulate the physical phenomena of a laboratory setup with a software on a computer and do not make use of any laboratory equipment. Students perform virtual experiments by interacting with the control interface of the software and observing the simulated results. Collectively, remote experiments and virtual laboratories will be referred to as e-labs throughout this article. The e-labs concept has also been discussed at several conferences dedicated to the subject, such as REV and ASEE/IEEE frontiers in education.

B. *The Need for e-labs*

E-labs are a well established resource for learning and are now becoming widely adopted [1]. The University of Cambridge WebLabs [8], CMCL SRM web-suite, MIT iLabs [9], TU Berlin Remote Farm [10], University of Stuttgart VideoEasel [10], and University of Basel NanoWorld [11] are examples of the e-lab learning materials presently available. There are many factors motivating the rise of e-labs including concerns over the cost, space, and staff requirements for conventional labs, as well as health and safety risks. Using e-labs can enrich curricula by providing students with experiences that would be too hazardous or prohibitively expensive in a conventional setup. Furthermore, simulations can use unique visualizations to provide insight not available in conventional labs; this is particularly the case for phenomena that are not directly observable. For example, the "Falling Coil" simulation at MIT [12] allows students to see changing magnetic fields and current as a ring falls towards a magnet, thereby illustrating Faraday's and Lenz's laws.

C. *E-labs vs Conventional Labs*

Below we present a comparison of e-labs and conventional labs by examining a remote experiment case-study and a virtual laboratory case-study. We propose that conventional labs, remote experiments, and virtual laboratories can all be important assets in curricula; viewing these methodologies as complementary, we identify suitable applications of each. Previous research has demonstrated that e-labs can be equally effective as conventional labs, in terms of understanding of course material, and that students do not express a strong preference for conventional labs, sometimes preferring e-labs as scheduling and time constraints can be alleviated [13].

Some key issues in the debate about e-labs versus conventional labs are: collaboration, analysis of experimental data, learning by trial-and-error, guidance from instructors, familiarity with laboratory equipment, and authenticity of experience [13]. The resolution of these questions is a matter of implementation, with a few exceptions. For example, both e- and conventional-labs can support collaboration, with e-labs using text, voice, and even video to link students. The same tools allow instructors to provide guidance and assistance during e-labs. Students gain experience working with experimental data through both remote experiments and conventional laboratories, but not with virtual labs. Whether learning by trial-and-error is supported can vary across all three types of lab. In conventional labs, time, costs, and safety concerns are all constraints; in e-labs the parameterization of the interface may be a limiting factor.

In some subject areas, only conventional labs can provide “genuine” experience with laboratory equipment and practice, so some conventional laboratories must remain in the curriculum. This is particularly the case for labs that involve a kinesthetic element and require the development of specific motor skills to ensure success; where this is not the case, a high quality interface, simulating the controls on laboratory equipment, can do a great deal to enhance a student’s feeling of immersion in the lab and familiarity with laboratory equipment [2].

Finally, the authenticity of a lab is significant in preparing students for industry, motivating theoretical learning, and promoting student engagement. All three types of labs can provide an authentic experience as illustrated by the case studies below. The SRM web-suite case study demonstrates that a virtual laboratory can provide an authentic experience, an observation that, to our knowledge, has not been demonstrated previously.

II. The Cambridge WebLabs

A. Background

The Cambridge WebLabs were set up using funding and support from the ‘Cambridge-MIT Institute’ initiative which was carried out between 2000 and 2006. During the development of the ‘iLabs’ network [9] between 1999 and 2006, the Massachusetts Institute of Technology (MIT) obtained significant experience in using remote experiments for practical teaching of Engineering and Physical Sciences subjects. The Weblabs project itself started in 2003 after a Cambridge student who had visited MIT suggested that the Department of Chemical Engineering at Cambridge should develop remote experiments of its own. Within two years, Cambridge had developed an advanced remotely operated apparatus for teaching of Chemical Engineering and was exchanging usage of its new facility for usage of similar apparatus at MIT [14]. The apparatus has since been utilised successfully by a number of institutions within the UK.

B. Laboratory Setup

The Cambridge WebLabs teaching rig (Fig. 1) consists of a stirred reaction vessel with three pumped feed lines and an adjustable outlet overflow. The feed pumps and stirrer are controlled by a SIMATIC^{TM} PCS7 interface (Fig. 2), which was donated together with the control software and hardware by Siemens Automation and Drives. The Siemens software and hardware is extensively used within industry and was chosen to help deliver an authentic educational experience.

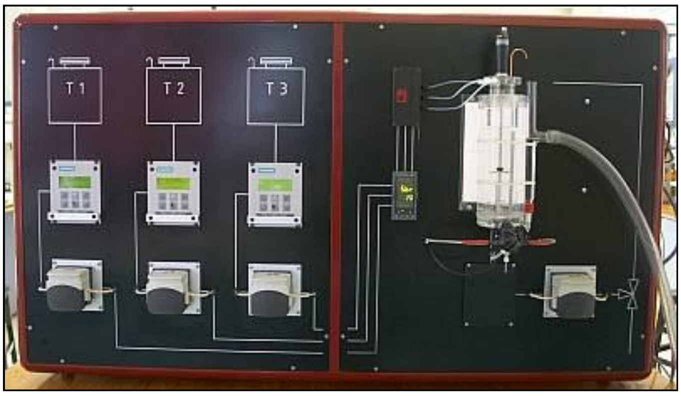

Figure 1. Hardware used in the Cambridge WebLabs

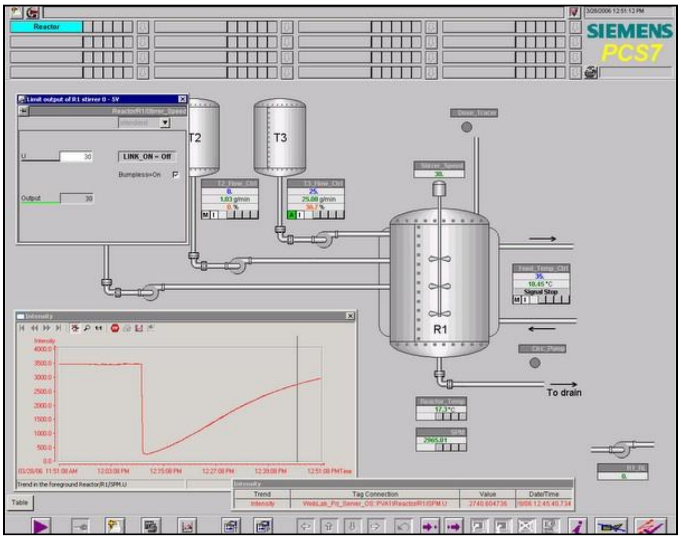

Figure 2. The SIMATIC^{TM} PCS7 interface

So far, two WebLabs experiments have been developed: one on chemical reaction engineering and one on process control. The reaction WebLab was developed by Cambridge alone, but the control WebLab was developed as a result of collaboration with the Chemical Engineering department at Imperial College, London. Both experiments make use of the slow equilibrium reaction between aqueous phenolphthalein and hydroxide ions which is observed at high pH and results in increased or reduced intensity of the characteristic pink color of the solution:

$$\mathrm{PHEN}^{2-} + \mathrm{OH}^{-} \underset{r_2}{\overset{r_1}{\rightleftarrows}} \mathrm{PHENOH}^{3-}$$

(pink) (colorless)

The intensity of the color of the solution is monitored by a photospectrometer and the readings can either be used diagnostically in the reaction experiment or for control purposes in the control experiment.

C. Usage

Since 2006, the WebLabs have been an assessed part of the Chemical Engineering course at Cambridge. In the case of the reaction engineering WebLab, students are required to complete a series of challenging theoretical exercises before they are permitted to use the apparatus. The exercises are designed to provide direction and focus to the experiment so that students can see their predictions tested and validated by following a rigorous procedure. In the process control WebLab, the preparation exercises are much simpler and students are given the freedom to try out a wide range of control parameters. The two experiments therefore use two very different pedagogical models.

So far, the WebLabs have been adopted in undergraduate teaching at the UK universities of Birmingham, Newcastle, and Surrey and Imperial College, London. The collaborating institutions have generally made use of the same supporting material and exercises as Cambridge.

D. Student & Institution Feedback

Student feedback on the Cambridge WebLabs (Figs. 3-6) has generally been good. The data in Figs. 3 & 4 use the Likert scale (1 = strongly disagree, 7 = strongly agree) and were collected for the class of 2008/2009. Most students responded that the WebLabs met their educational learning objectives and that they were a beneficial learning experience. However, the WebLabs proved less successful in capturing students' imaginations, as most users did not find either exercise significantly more (or less) enjoyable than other course work at a similar level. When used at other institutions, feedback on the WebLabs was mixed; in those cases, some students struggled to complete the preparatory exercises, which are tailored specifically to the Cambridge course.

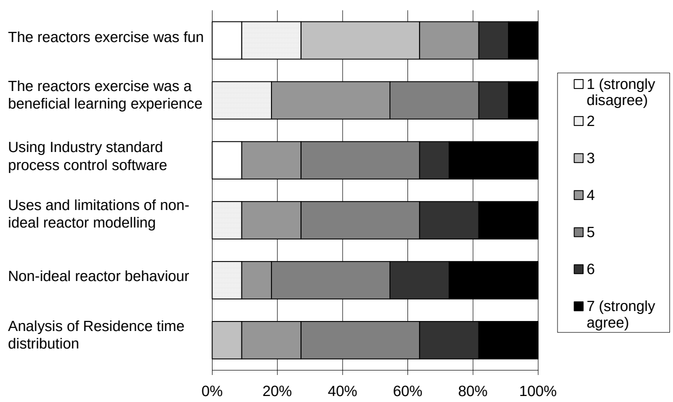

Figure 3. Feedback from the reaction engineering exercise

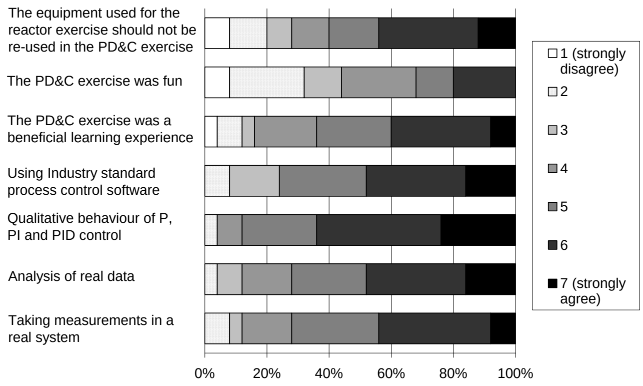

Figure 4. Feedback from the process control exercise

E. Sustainability

The concept of online learning through remote experiments has been demonstrated to be technically viable, but experience running the WebLabs at Cambridge has highlighted that the following problems need to be mitigated to ensure their sustainability:

- Unlike virtual laboratories, remote experiments have significant maintenance costs.
- It can be difficult for other institutions to use remote experiments as coursework exercises because it costs time and money to integrate them into their curricula.
- Universities' teaching times often coincide, meaning that only a small number of institutions can use a given remote experiment as part of their undergraduate course; the fact that only one user group can operate the experiment at a time is a significant limitation.
- Although interested in using each others' remote experiments, institutions may initially be unwilling to pay for that use, because e-labs are not yet a well established component of coursework.

Remote experiments are therefore most likely to be adopted by sharing facilities between a number of institutions that have the resources to develop them. It is also desirable to build experiments which have value for industrial research or testing, as rental of facilities to companies during universities' holiday periods could play a major role in ensuring sustainability.

III. THE SRM WEB-SUITE VIRTUAL LABORATORIES

A. CMCL Virtual Laboratory Methodology

The SRM web-suite is a series of virtual laboratories, developed by CMCL innovations, that focuses on combustion in engines, enabling insight into state-of-the-art combustion processes and futuristic fuels. The key innovation of the CMCL methodology for virtual laboratories is its basis of virtual labs for education using industry-standard research and development (R&D) tools. The simulations in the SRM web-suite use the same technology as CMCL's SRM suite [15], which has been adopted by R&D teams at engine manufacturers in order to improve engine performance and emissions and streamline the development process by reducing the number of costly experiments performed.

The SRM web-suite represents a new development in e-learning tools by being simulation-based yet providing students with an authentic experience. Simulations for virtual laboratories are usually developed strictly as educational tools, simplifying many details to ease the implementation or emulating simple experiments that students could have carried out in a conventional lab. Thus, the authenticity of a student's experience is sometimes diminished through the use of a virtual laboratory. In contrast, the SRM web-suite offers students experience with real industrial tools used in combustion, emissions, and engine development research. Moreover, the SRM web-suite provides students with the opportunity to perform experiments that would be otherwise inaccessible due to the safety, cost, and time constraints associated with an equivalent conventional lab. For instance, studying the characteristics of an unstable engine mode such as "knocking" in a conventional engine lab set up can be potentially hazardous because of the possibility of severe engine damage. The same phenomenon can be studied in a cost-effective and safe manner using the SRM web-suite.

B. *Technical Architecture of the SRM web-suite*

The architecture of the SRM web-suite is based on a client-server model in which simulations run on a remote server, either one of CMCL's servers or a licensed server deployed at an academic institution. Students then interact with a lightweight web-interface implemented as a Rich Internet Application (RIA). The only requirement for a student's system is a Javascript enabled web-browser, allowing any platform to be used, including mobile devices. This flexibility and convenience may encourage students to make more use of any optional laboratory components in a course. For example, enthusiastic students could entertain and educate themselves by carrying out SRM web-suite labs using their smartphones, whilst waiting for a bus. The client server-architecture and lightweight RIA interface allow new customized interfaces to be deployed easily to support new educational modules, while employing the same underlying simulation technology. This means that a larger portion of development time can be spent creating valuable supporting materials, rather than being consumed by technical developments.

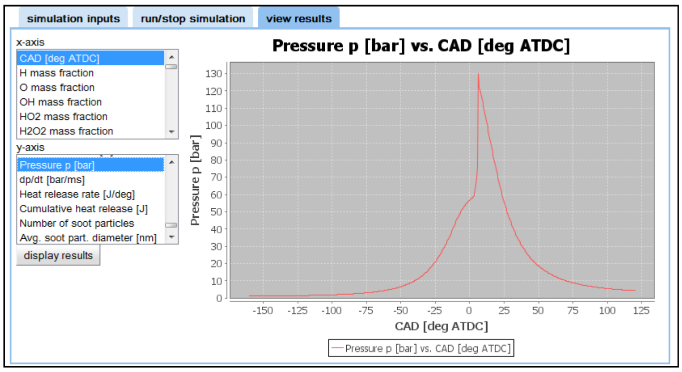

Figure 5. Screenshot showing simulation data from a web-suite laboratory

C. *Pedagogical Methods*

The methodology and architecture described in the previous section provide the SRM web-suite virtual laboratories with a flexible structure that can accommodate a range of pedagogical models and educational goals. The same simulation technology, provided with different user interfaces, can be used to teach introductory undergraduate courses on combustion engines and advanced seminars on future fuels.

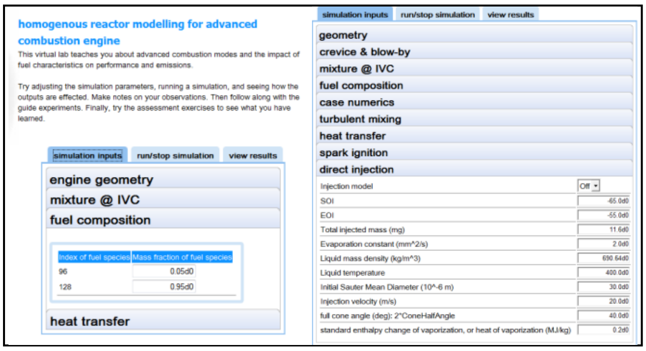

Figure 6. Web-suite interfaces for an introductory lab (left) and an advanced lab (right)

One key feature of the SRM web-suite virtual laboratories is that students can learn by trial-and-error, using the "productive failure" pedagogical method. Recent research has demonstrated that students retain a significantly higher portion of content using this methodology [16,17,18,19,20] in which they are first posed with an undirected task that they *attempt* to solve through experimentation and observation, followed by periods of increasingly guided learning during which their success rate increases. The web-suite labs enable a productive failures methodology to be used because there is no limitation on the number of times a student can run the simulation and no significant growth in cost with the increasing number of runs.

In the case of a conventional or remote experiment, there is often a cost (in materials and/or manpower) associated with each time the experiment is run; this requires that limits be placed on the extent to which trial-and-error learning can be employed. For example, each run of an experiment on the Cambridge WebLabs reactor uses chemical supplies which must be purchased and maintained by laboratory staff. Scheduling also constrains the use of trial-and-error learning in conventional and remote experiments, because access to laboratory equipment, whether direct or remote, must be shared between students. This is not the case with the SRM web-suite virtual labs, since students can perform the experiment at their convenience, repeating it as many times as they need, and any number of students can be performing the experiment simultaneously (up to the limitations of the server running the simulations). The ability to repeat experiments or perform them at a slower pace may also benefit students with different learning styles or rates.

In addition to use in a productive-failure framework, the SRM web-suite virtual laboratories are also ideally suited to more traditional guided methodology, or for demonstrative purposes as a part of lectures. The client interface can be augmented with guided interactive support at various levels, to provide additional information or to take the student through an experiment step-by-step. The design of the client interfaces for the web-suite labs makes it easy to embed them into larger modules and to incorporate a range of supporting materials such as videos, diagrams, and assessment exercises.

Finally, the SRM web-suite can be used for collaborative student work; however, collaboration tools are not currently a core feature in the virtual laboratories. Collaboration features are being included as part of the European Commission's Libray of Labs (LiLa) portal through which the SRM web-suite can be accessed, as described in Section IV.

IV. Remote Experiments or Virtual Laboratories – or Both?

A. Pedagogy

The pedagogy which is usually associated with remote experiments is very different from that associated with virtual laboratories. In remote experiments, students are usually required to follow strict procedures in order to complete an experiment safely and on time. This promotes strong organizational skills, can be used to enable team working skills, and helps to develop students' intuitive understanding of the physical world through interaction with the equipment. Virtual experiments have few constraints with regard to time and safety, and are well suited to an exploratory style of learning, which teaches fundamental concepts and improves theoretical understanding. Nevertheless, more advanced virtual laboratories, such as the SRM web-suite, can offer a good compromise between remote experiments and historical virtual laboratories. They require significant computing power, so run times are not insignificant, but are highly realistic in terms of the data generated and their relevance to industry. This means that they have many pedagogical similarities with remote experiments or real laboratories.

B. User Experience

It has been argued by some [13] that for many applications, remote experiments can provide learning outcomes which are of equivalent value to conventional laboratories. Others [2] broadly agree with this conclusion, but would insist that a balanced approach is still valuable as simple hands-on experiments can allow better collaboration and interaction with the equipment. They would nevertheless advocate remote operation if there are compelling pragmatic reasons (see section IV-C).

Student feedback from the Cambridge WebLabs suggests that the typical user is indifferent to remote experiments in terms of their enjoyment, although they are usually satisfied with the learning outcomes that they deliver; the findings of [13] would support this conclusion. It must also be stressed that the usage of an industrial interface was generally appreciated by the users of the Cambridge WebLabs and to some extent mitigated the students' negative views.

According to an old view which is perhaps becoming outdated, virtual laboratories are much easier to package in an attractive and exciting user interface which promotes user engagement, however their lack of relevance to the physical or commercial world limits their value as a learning tool for higher education. The next generation of virtual laboratories (e.g. the SRM web-suite) is designed to address these weaknesses by aiming for a higher overall level of authenticity.

C. Technical requirements & Sustainability

Virtual laboratories offer a major advantage over remote experiments in that their design costs are lower and that their maintenance costs are almost non-existent. By contrast remote experiments can be relatively expensive to set up, even when resources are shared between institutions, and maintenance costs are significant and ongoing. Furthermore, remote experiments are much more likely to experience 'downtime' than virtual laboratories. Virtual laboratories are therefore inherently more sustainable than remote experiments.

In the case of experiments which involve sophisticated equipment and are a standard part of a taught course, there is are strong pragmatic reasons why universities may wish to pool resources by using remote operation. As well as reducing costs, this reduces the risk that equipment will be left in a poor state of repair, thus allowing students to focus on the scientific aspects of their experimental work.

D. Usage & Integration into Curricula

It has been suggested [10] that there are significant benefits associated with combining remote experiments and virtual laboratories. By comparing real experimental and virtual experimental results, it is possible for students to gauge the strengths and weaknesses of different modeling techniques, thus creating a very powerful teaching tool. Design of these combined experiments is time-consuming and expensive, but the potential for sharing resources between institutions may well make this approach viable if there is sufficient interest. Although the Cambridge WebLabs have not yet reached this state of development, the combination of in-depth theoretical pre-preparation and practical experimentation is a step closer to the goal of combining remote and virtual experiments.

V. Future Work

A. The LiLa Project

The Library of Labs (LiLa) project is a pan-European initiative to develop a network of e-labs and supporting materials aimed at undergraduate and graduate students; the LiLa project is co-funded by the European Commission in the context of the eContentplus programme. Among the scheduled developments in the LiLa project is the LiLa web-portal, the entry point for access to the e-labs and other content in the LiLa network. The LiLa portal will provide supporting infrastructure for e-labs such as search and retrieval functions to find appropriate e-labs and related content and a booking and access control system to share and protect the equipment in remote experiments. Pedagogical support provided by the LiLa portal includes collaboration tools and a tutoring system to guide students in their studies and suggest related. The collaborative aspect of the portal will enable group work and interaction between students, but will also increase student interest by taking advantage of the social habits and technologies of the Web 2.0 generation. LiLa content will be delivered as SCORM packages, allowing integration into local learning management systems (LMS).

B. Projected impact of LiLa on WebLabs and SRM web-suite

Participation in the LiLa network will benefit developers of e-labs in a number of respects. Firstly, the infrastructure and pedagogical functionality in the LiLa portal can be used to enhance e-labs. For example, one of the difficulties that Cambridge faced, when its Weblabs were used at other institutions, was a lack of appropriate supporting materials; the materials provided were not necessarily appropriate for use at other institutions. Through the LiLa network, lecturers and institutions can develop and share supporting materials for e-labs, reducing the initial cost of integrating an e-lab and ensuring that a range of supporting materials are available. Looking at the CMCL case study, users of the SRM web-suite labs will benefit from the collaboration tools, additional resources, and community support offered by the LiLa network. The development cost of these tools for a single e-lab would in many cases prove prohibitively expensive, but becomes viable when shared between many users.

In addition to the resources provided by the LiLa network, its user-base may also be beneficial for e-lab providers. One of the major difficulties with e-labs is balancing their high costs in the case of under-utilization. By opening up an e-lab to a wider audience, its utilization can be drastically improved; greater usage lowers the per-user running costs, which can potentially be distributed over a number of institutions using the e-lab.

VI. Conclusions

A comparison between a remote experiment, 'Cambridge Weblab' and a virtual lab, 'SRM web-suite' was presented in this paper.

It is almost certain that virtual laboratories will continue to play a major role in the teaching of engineering and physical sciences in the future, due to their convenience and low costs. Educational applications of more sophisticated virtual laboratory technology, such as the SRM web-suite will ensure that students are well prepared for industry, which is making increasing use of simulations to reduce the need for expensive and time-consuming experimental programmes. Nevertheless, this approach also entails that the students need to know the limitations of different modeling and simulation techniques if they are to successfully apply them.

Remote experiments can provide authentic laboratory experiences, essential for student's educational development. Many universities will struggle to find the resources to provide more than a small number of conventional experiments, so remote operation of others' facilities is a potential solution to this problem.

Initiatives such as the LiLa project are essential in order to provide a systematic framework for enabling a collaborative usage of remote experiments and virtual laboratories to meet the educational needs of today's students.

Acknowledgment

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