The TriLab, a Novel View of Laboratory Education

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Keywords: The TriLab, Engineering Education.

Abstract: Laboratory education is an important side of engineering and science degrees. However, the related literature has frequently reported that laboratory education is suffering deficits. Recent advances in Information and Communication Technology (ICT) have contributed to laboratory education by creating two new modes, the virtual or simulated mode and the online controlled mode. Blending the virtual lab and the online lab with the classical hands-on approach of conducting laboratories may enrich the experiential education in many ways. In this paper, we introduce a new model of laboratory education, namely the TriLab. The TriLab is a triple approach of conducting laboratories in which students are exposed to the virtual, hands-on, and remote laboratory. The initial architecture of the TriLab has been developed and a pilot study has been conducted in the second year module Instrumentation and Control at the Chemical Engineering Department at Loughborough University. Initial quantitative analysis showed that using the virtual lab in pre lab session have increased the students interest in working more beyond the planned hands-on lab session, while using the remote access in classroom lecture for demonstrating theory has been found helpful by the students on understanding the theory in better way. The results presented here indicate that the TriLab paradigm can have a significant impact on laboratory education in engineering subjects.

Introduction

The importance of a laboratory experience in engineering education curricula has been emphasized in a large number of science and engineering education articles (Johnstone et al. 2001; Hofestein et al. 2004; Feisel et al. 2005; Kirschener et al. 1988; Ma et al. 2006). The essential role of laboratories can be correlated with the fact that engineering is, in general, an applied science that requires very good hands-on skills and involves elements of design, problem solving, and analytical thinking. Well designed laboratories during undergraduate engineering degrees can improve these skills for graduate engineers.

Engineering started as a result of the accumulation of hands-on experiences (it had been taught as pure hands-on up to the 18th century). However, engineering education has benefited from advances in science and it began to embed deeper theoretical concepts by the end of the 19th century, for example in the US schools (Feisel et al. 2005). Since then, the pedagogical emphasis in engineering education has shifted more towards classroom and lecture based education, while less
attention has been given to the laboratory education particularly during the last 30 years (Hofestein et al 2004; Hofestein et al 1982; Feisel et al 2002). Wankat observes that only 6% of the articles published in the Journal of Engineering Education from 1993-2002 had ‘Laboratory’ as a keyword (Wankat 2004). But, laboratory pedagogy has been recently reported to be a fertile arena of research for the coming years (Feisel et al 2005; Hofestein et al 2004). Especially in the need to make more use of the new developments in information and communication technology (ICT) for enhancing the laboratory education.

The impact of laboratory education on student learning is often not recognized (Roth 1994). One reason for rethinking the role of the laboratory in engineering and science education is the recent shift towards constructivist pedagogy which embraces the philosophy of considering the essential role of experience in knowledge construction and places a more important role on student autonomy in the learning process. One important contribution of laboratory education in the engineering curricula is ‘enjoyment’ as a motivating factor for students which has been reported in many studies during the last few decades (Hofestein et al 2004). This is particularly important in view of the recent increased number of demanded engineers in the industry and the continuous drop in student numbers taking engineering and science courses.

**Hands-On Laboratories**

It is commonly accepted in science and engineering that the laboratory should help students with conceptual understanding and in constructing new knowledge. In his literature review, Ma found that 100% of the articles concerning Hands-on Laboratory (vs. simulated or virtual labs) considered that the laboratory should be a platform for facilitating conceptual understanding, and 65% considered that the laboratory should also facilitate design skills. However, the process of constructing knowledge is complex and in many cases, it occurs beyond the time frame of the planned laboratory session. Constructivists consider learning as an iterative process (Kolb 1984). Meaningful learning needs reflection (Hofestein et al 2004). Many researchers have noticed that these practices are lacking in classical hands-on laboratories. Gunstone (1991) considered laboratories that were taught in the classical way to be barely a platform of knowledge construction, since students have less time to interact and reflect while they are busy with the technical and the operational side of the laboratory. Kirschner et al (1988) reported a general consensus that laboratory work generates poor learning outcomes compared with the time, effort, and costs invested in the laboratory. This complaint has been reported in many recent studies on laboratory education (Johnstone et al 2001; Hofestein et al 2004; Ma et al 2006). Nevertheless, the importance of hands-on laboratories is recognized because of its important role in showing students how theory is applied in practice (Kirshner 1988). Most students prefer to do hands-on experiments instead of any equivalent computer simulations due to the realism factor. However, conducting hands-on experiments has many disadvantages such as constraints on time, resources, maintenance, expensive equipment, and safety hazards.

**Virtual (simulated) Laboratories**

The first virtual experimentations (or simulations) in an educational setting in the UK took place in 1962 when a computer simulation was used in the first year undergraduate course on nuclear engineering at Royal Naval College, Greenwich. In
the same period, similar trials were conducted in the US, too (Smith 1992). Furthermore, many other institutes began to use computer simulations in the UK and the US, for instance a computer simulation for electrical power engineering course at Queen Mary College was used during 1970 (Smith 1976), and simulations for nuclear engineering students at the same university were used in 1971 (Smith 1981). Since then, the literature has frequently reported the positive impact of using computer simulations in the educational process (Kinzel et al 1981; Adams 1981; Campbell 1985; Libowitz et al 1987; Laghari et al 1990; Jimoyiannis et al 2001). More recently, engineering simulation software systems are integral to engineering education and the design process. Indeed, computer software systems can be called virtual laboratory platforms, examples are SPICE and MATLAB/SIMULINK (PSPICE 2008, Mathworks 2008).

Computer simulations have many advantages. For example, they offer a safe environment for students to test hypotheses and investigate outcomes. Students can use them outside class time for reflection and self testing, while teachers can save their contact time with the students by fostering the simulations. Simulations can be an alternative for conducting unavailable experiments because to high costs and provide a way for conceptual learning to occur avoiding the technical complexities of real test rigs. Virtual experiments allow students to perform sophisticated practical experiments that otherwise would require a high physical or technical level. Further, virtual simulations can be the instrument for testing hypothesis and can avoiding experiments which may have difficulties in ethical difficulties, such as animal experiments. However, there is general agreement that simulations can not and should not always replace the hands-on laboratories. Simulations lack the realism factor, students do not have the same belief and level of responsibility in simulated experiments as in the case of hands-on laboratory sessions.

Online (Remote) Laboratories

The most recent laboratory paradigm is the so called online-laboratory in which students can physically perform hands-on experiments which are located at a place remote to the student, typically via Internet access. The idea of implementing controlled laboratories through the Internet for educational purposes can be tracked back to the 1991 when Aburdene and others suggested a futuristic solution for sharing laboratory equipments through the Internet (Aburdene et al 1991). They expected that this model would be used for operating experiments in the classroom and would be a facilitator for sharing experimental resources among institutions. An implementation of remotely controlled robots which was scattered over four universities in the US and NASA was successfully tested in 1993 (Kondraske et al 1993). Another early application was an Internet based control laboratory which was implemented in Oregon State University (Aktan et al 1996). Since then the number of Internet based laboratories has rapidly increased and the geographic distribution spread to Europe, Australia, and East Asia. A review of available online laboratories is presented in Appendix 1.

One advantage of developing an online laboratory is the ability to share resources with other partners, which eliminates the economic cost of buying new hardware for the institute. Online laboratories shared among many universities could enrich the experiential education of students as they would have a large database of laboratories to access. The cost of new experimental rigs is significant to a higher education institute’s budget. This is particularly true in some engineering disciplines where technology is advancing quickly and there is a continuous need to follow and embed these advances in the curriculum. This pressure led in the 1970s and 1980s
to a move among some institution administrators to minimize the laboratory work in the undergraduate curricula (Kirschner et al 1988). Many researchers have described the economical benefits of implementing more online laboratories (Kondraske et al 1993; Ma et al 2006). One example of sharing experiments located on two different continents is the Cambridge-MIT remote experiment (Colton et al 2004). Some companies now offer a database of remotely accessed experimental rigs located at different partners to be accessed for a small fee. It has been reported in many papers that online laboratories have stimulated the students enthusiasm towards the studied subject since the labs were presented in a non-conventional way (Aktan et al 1996; Ma et al 2006). There are many other advantages of online laboratories, such as offering real experimentation for distance learning students, accessing remotely hazardous locations or flexibility in delivering laboratory experience.

The TriLab, a Hybrid Laboratory with Triple Mode Access

There is no general agreement as to the effectiveness of one or other mode of laboratory access. For instance, in a study of the effectiveness of remote laboratories, it has been quantitatively found that remote students achieved about 5% to 8% lower grades than those of the hands-on students. Generally, they also needed more time to finish the experiments (Sicker et al 2005). However, contrary results obtained by other researchers have also been reported. Carter et al (2004) in a comparative study on online versus hands-on labs found that most students who used the remote labs obtained similar or even better results in the tests than those who used the hands-on lab.

There is general agreement that simulations can not and should not always replace the hands-on labs, however, it can be an effective assisting tool. Engum et al (2003) made a comparative study on using a virtual catheter lab versus a real catheter lab. The study revealed that students who performed both the real lab and the virtual lab could adequately demonstrate the required skills, however, the students preferred performing the real lab against the virtual lab. Engum suggested that a combination of the two methodologies may enhance the students satisfaction and skills acquisition level.

![Figure 1. Conceptual model of the TriLab.](image)

To date, and according to our knowledge, there is no one hybrid lab that utilizes hands-on, virtual, and remote modes in one stand alone complementary package. There have been trials embedding two modes together in the pedagogical processes (Engum et al 2003; Tzafestas et al 2006), indicating better learning outcomes in the hybrid labs. Raineri (2001) supplemented his hands-on lab with a simulated lab. Using the simulated lab with the course over five years yielded a five percent increase in the final exam scores, and a dramatic decrease in the number of students who either failed or passed only with the minimum threshold. The same article
emphasized the importance of the hands-on lab, and suggested that the simulated laboratory is rather a supplement, but yet an important addition to the module. Very similar conclusions can be found in Ronen et al (2000) and McAteer et al (1996). Tzafestas implemented two modes, a simulated and remote hybrid telerobotic lab, this combination was found to be effective (Tzafestas et al 2006). One of the most important conclusions in the Ma comparative literature review of the Hands-on, Simulated, and Remote labs is the importance of taking advantage of using the different access modes as much as possible (Ma et al 2006), this is an indication of the recent research awareness of enriching the laboratory education by blending different access modes instead of relying mainly on one access mode, which classically was the hands-on lab experiment so far.

There is no argument as to the importance of the hands-on laboratory in engineering education (engineering itself started as a hands-on science). Despite the disadvantages of hands-on experimentation, they still provide the highest realism and concept level for students. Virtual laboratories have been found to be powerful in increasing conceptual understanding. They offer a cheap instrument for repeating experiments as many times as a student requires. However, they are characterised by weak realism. The birth of online experimentation and conferencing techniques have added a new dimension to the way engineering projects can be dealt with. Furthermore, there is strong potential for enhancing the experiential engineering education experience of students through the sharing of the experiments and the practice of completing those experiments. Embedding online experimentation in the engineering curricula could become a necessary step sooner or later to meet the increasing demands for online operation and collaboration of future engineers and researchers. The paper analyses, by case study, the TriLab laboratory paradigm that is introduced as a hybrid model that utilizes the three different access modes discussed above. Figure 1 shows a conceptual model of the TriLab system.

Figure 2. Process control test rig.
Figure 3. Graphical user interface of the developed educational software.

Case Study, The Process Control Laboratory

The TriLab model concept has been applied for the teaching of the second year Instrumentation, Control and Industrial Practice module at the Chemical Engineering Department at Loughborough University. The experimental rig of the hands-on process control lab was designed to mimic a real surge tank system which is a typical chemical engineering process. Figure 2 shows a picture of the hands-on test rig. The laboratory is a compulsory part of the module designed for undergraduate MEng, BEng, and BSc programmes in chemical engineering at Loughborough University. The lab aimed to introduce students to the principles of control engineering, such as the main components and instruments of a feedback loop, the concept of open-loop control, feedback control, proportional-integral-derivative (PID) control, and PID tuning. The software interface for the experimental rigs, the virtual version of the process control lab as well as the remote version were developed using LabVIEW.

Figure 4. Conceptual model of the experimental methodology.
(National Instruments (LabView 2008). The simulation mode was mainly designed to give students the opportunity to practice and prepare the lab in advance by means of simulation of the real plant. The real-time mode allows for the performance of the actual experiment in the classroom. It also enables users to remotely access a surge tank control plant in order to execute experiments locally or remotely. Figure 3 shows the graphical user interface (GUI) of the developed educational software (package can be downloaded from (Nagy 2008)

The remote access laboratory component of the TriLab was used during the lecture to illustrate the theoretical concepts. Students were asked to download and install the Virtual Process Control Laboratory, and undertake exercises before the hands-on laboratory session. In addition, pre-lab training sessions were organized using the virtual laboratory.

Virtual Lab Impact. To measure the impact of the virtual laboratory on students’ learning, the class of 70 students was divided into four groups distributing the students evenly based on their GPA (Grade Point Average) in their first academic year. The first two groups used the hands-on laboratory only and they were considered as the control group. Whereas students in the third and fourth groups were asked to perform a preparation session using the virtual lab before doing the hands-on lab. About 60% of the third and fourth group students responded by doing the virtual lab in advance. They are considered as the experimental group. Figure 4 shows a diagram of the experimental methodology followed.

For evaluating the impact of the virtual and hands-on labs, pre-lab and post-lab tests were conducted. Students were also asked to fill in a questionnaire after the lab sessions as well as a generic questionnaire at the end of the semester.

One of the questions in the questionnaires was: “Would you like the idea of conducting post lab real experimentation through the Internet (i.e. from your home PC) after the lab for enhancing your report or testing further ideas?”, to which students could respond with a mark from 1 (not at all) to 6 (very much). Figure 5 represents the students answers distribution. The responses of the two groups differed considerably, the average of the control group is 4.19/6 while the average of the experimental group is 5.27/6.

![Figure 5. Answer distribution of the control group (a) and the experimental group (b)](image-url)
Figure 6. Cambridge Experiment at Loughborough.

To evaluate whether the difference in the means has statistical significance and is not due to coincidence the null hypothesis ($H_0$) test was used. The Mann-Whitney non parametric test, yielded the Exact Sig value of 0.027, which is smaller than the limit of 0.05 for 95% confidence. This small value indicates that the null hypothesis can be rejected, demonstrating that the preparation session using the virtual lab introduced for the experimental group has a statistically significant impact on motivating students towards further inquiry and experimentation.

We also noticed a different behaviour during the laboratory in the case of students from the experimental group compared to the control group session. Those students who undertook preparation using the virtual lab showed more interest in the hands-on lab session and insisted on answering the pre- and post-lab tests compared to the control group students and provided significantly better answers in the tests.

Remote Experiments in The Classroom. One important pillar of constructivist pedagogy is to expose students to authentic real-world problems (Doolittle 1999). This implies relating theory taught in the classroom to practice and illustrating theoretical aspects in an authentic real environment. Conducting a real experiment in the classroom is one perfect example of exposing students to real settings while they are taught theory in the classroom. However, this is impractical in most cases since most experimental rigs are difficult or impossible to be transported to the classroom. A remedy of this can be through remote experimentation. Here in the Chemical Engineering Department at Loughborough University, we tested the remote experimentation in the classroom as a method for supporting students understanding of the theoretical concepts. Several experiments have been conducted both in undergraduate (second year Instrumentation and Control) and Master level classes. In the first pilot test, conducted during the spring semester in 2007 in the Batch
Figure 7. Students’ answers to the question whether they consider that the use of remote laboratory has enhanced their understanding.

Processing MSc module, the remote experimental rig provided by the Cambridge-MIT institute was used. The aim of the experiment was to introduce students to the importance of automatic control of chemical batch reactors, making them familiar with the real application of a PID control algorithm using a real industrial operating interface. The remote experiment was accompanied with video transmission to create the feeling of being present (telepresence) in students. The snapshots shown in Figure 6 illustrates the user interface and video window captured during the experiment. Students were asked to answer the following questions at the end of the lecture;

“What do you think about the idea of explaining theoretical concepts of the lecture by presenting real remotely controlled experiments?” Most of the students, 77.7%, declared a positive attitude towards conducting remote experiments in the classroom, about 22.3% declared dissatisfaction for the short time that was dedicated for the experiment.

The undergraduate pilot experiments were conducted in autumn 2008. In the remote experiments the process control rigs from the department were used on several occasions. Students were asked whether they found the application of the remote laboratory during the lecture useful for enhancing their understanding of the topic. The majority of students, 78.1%, answered: “YES it is useful” as shown in Figure 7.

The pilot studies provide strong evidence that remote classroom experimentation is good constructivist practice since it exposes students to real authentic phenomena, and describes how theory is applied in a real context. This could be a driving force toward deeper meaningful learning in the lecture and a motivation for further investigation. It is planned that in future tests the remote labs will be made available to students to perform after-lab experiments if they want to develop further their understanding before they have to hand in the laboratory reports. Moreover, after-lab assignments will be introduced in the curriculum of the module.

Conclusions

The paper describes a new model of laboratory education in which virtual, hands-on, and remote access modes are combined to contribute to the learning process of the students. Each mode has its own advantages and disadvantages; blending the three
modes into one entity may lead to maximizing the learning outcome as well as motivating students towards constructivist learning. The pilot studies conducted within undergraduate and taught postgraduate students in the Chemical Engineering Department at Loughborough University demonstrate the benefits of the TriLab paradigm. In this pilot study, the virtual lab has been used in pre-lab preparatory sessions, statistical inference showed that using the virtual lab in pre lab session has lead to motivating the students towards further experiential learning, however, we are not sure yet what is the exact mechanism behind this motivation. The remote lab has been used to bring the live hands-on lab into the classroom for linking theory to practice, the students opinion survey showed positive impact of classroom experimentation as well as desire of extension of this experimentation in another courses. In the future additional post-lab assignments through the remote laboratory rigs will also be introduced, and a detailed quantitative analysis will be performed on the role and contribution of each individual component in the success of the TriLab paradigm. Furthermore, we intend to study the correlation between students learning style and the preference of one access mode over another.

**References**


## Appendix

List of online labs

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