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The TriLab, a novel ICT based triple access mode laboratory education model

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ABSTRACT

This paper introduces a novel model of laboratory education, namely the TriLab. The model is based on recent advances in ICT and implements a three access modes to the laboratory experience (virtual, hands-on and remote) in one software package. A review of the three modes is provided with highlights of advantages and disadvantages of each mode. It is shown that recent literature on laboratory education recommends hybrid structures. Some literature has reported on the use of two modes hybrid structures, however, it is seldom reported to have triple access mode laboratory. This paper probably the first to report empirical findings of using the three components together. The virtual component of the TriLab has been mainly used in a preparation session for undergraduate students, while the remote component has been mainly used for demonstrating theory applicability in postgraduate courses. The empirical findings shows clearly the positive impact of the hybrid approach on students learning and motivation, these are discussed in light of pedagogical and cognitive psychology theories.

1. Introduction

The importance of laboratory education for engineering and science has been strongly stressed in the literature (Chu & Lu, 2008; Corter, Nickerson, Esche, & Chassapis, 2004; Dechsri, Heikkinen, & Jones, 1997; Feisel & Rosa, 2005; Hofstein & Lunetta, 2004; Johnstone & Al-Shuaili, 2001; Kirschner & Meester, 1988; Ma & Nickerson, 2006; Tan, Lee, & Leu, 2000). The hands-on laboratory sessions and practical training remained much more important than theory and mathematics in engineering curricula until World War I (Wankat, Felder, Smith, & Oreovicz, 2002). Since then, the pedagogical emphasis in engineering education has been shifted more towards classroom and theory lecture-based education. Gradually, less attention has been given to laboratory education, particularly during the last 30 years (Feisel & Peterson, 2002; Hofstein & Lunetta, 2004, 1982). Laboratory pedagogy has recently been reported to be a fertile arena of research for the coming years (Feisel & Rosa, 2005; Hofstein & Lunetta, 2004), especially in the context of further utilization of new developments in information and communication technology (ICT) for enhancing laboratory education.

The classical form of conducting laboratory education involves the physical presence of the individual at the experimental rig. This is generally referred to as the *hands-on laboratory* in the literature (Ma & Nickerson, 2006). Hands-on labs are sometimes also called proximal labs (Lindsay & Good, 2005). Hands-on laboratories promote the most important aim of using experiments in the educational process, which is to provide the feeling of realism, e.g. the sense of dealing with a real physical plant. Affective factors play an important role in the learning process. Many studies relate the significantly higher order learning or behaviour in real settings vs. virtual settings to the realism factor (Heise, 2006; de Kort, Ijsselsteijn, Kooijman, & Schuurmans, 2003). Witmer, Bailey, and Knerr (1996) state that better learning and training requires a higher level of fidelity and realism. The constructivist pedagogy literature frequently emphasizes the importance of an authentic and real or quasi real environment for learning (Richardson, 2003). Hands-on laboratories are particularly important for acquiring haptic skills and instrumentation awareness. Such skills are otherwise impossible or very difficult to obtain via virtual or remote labs.

Nevertheless, constructing knowledge is a complex process that can be out of the time frame of the planned hands-on laboratory sessions. Educationalists consider learning as an iterative process (Hmelo, Holton, & Kolodner, 2000; Kolb, 1984; Papert, 1980). Meaningful learning in laboratories does need reflection (Hofstein & Lunetta, 2004). These practices are generally missing in the classical teaching of hands-on laboratories, mainly due to time constraints (Kirschner & Meester, 1988). Hands-on labs are usually taught as one single demonstration for economical and logistical reasons. However, forming and understanding concepts requires more than a single

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demonstration (Kolb, 1984). The aimed impact of laboratory education on the students' learning is often not realized (Roth, 1994). Gunstone (1991) considers hands-on laboratories as poor platforms for knowledge construction, mainly because the students have less time to interact and reflect while they are busy with the technical and operational side of the experiment during the hands-on laboratory session. Kirschner and Meester (1988) relate poor construction of knowledge during a hands-on lab session to cognitive overload. Furthermore, students are constrained by the short periods normally available in the lab. Kirschner and Meester (1988) report that there is a general consensus that laboratory work generates poor learning outcomes compared to the time, effort and cost invested in the laboratory. These drawbacks have been frequently reported in laboratory literature (Hofstein & Lunetta, 2004; Johnstone & Al-Shuaili, 2001; Ma & Nickerson, 2006).

Recent advances in ICT during the last three decades have resulted in the emergence of two new modes of laboratory: *Virtual (Simulated) labs* which are approximated simulations of a process of a physical experimental rig. Examples of virtual labs can be found in Blanchard, Moron-Garcia, and Bates (2006); and *Online (Remote) labs* which are platforms that allow remote access to the physical experimental rig through the Internet or intranet. Examples can be found in Aktan, Bohus, and Shor (1996), Arpaia, Baccigalupi, Cennamo, & Daponte, 1997, Bauchspiess, Guimaraes, and Gosmann (2003), Callaghan, Jim, Martin, and Maguire (2008), and Nagy and Agachi (2004). In the literature, the term sometimes refers to remote labs (Guimaraes et al., 2003); however, in this paper, a virtual lab strictly refers to a computer simulation, whiles the term 'remote lab' or 'online lab' is used to refer to a remotely controlled physical rig.

2. Virtual (simulated) laboratories

Educators have been aware of the potential of computer simulation or PC-based virtual experiments in improving the educational process since the early days of computers. The first usage of simulation in an educational setting in the UK can be traced back to 1962, when computer simulation was used for illustration in a first year undergraduate course on nuclear engineering at the Royal Naval College, Greenwich. This took place almost at the same time as similar trials in the US (Smith, 1992). Later on, there were an increasing number of institutes where simulated experiments were used in the UK. Computer simulation software for electrical power engineering at Queen Mary College was developed in the early 1970s (Smith, 1976). Simulations for nuclear engineering students in the same university were used as early as 1971 (Smith, 1981). Computer simulations were used in a course on fluid mechanics and heat transfer taught at the Imperial College during 1974 (Gosman, Launder, Lockwood, & Reece, 1977).

Computer simulations became an integrated part of engineering and science education as early as the 1970s (Campbell, 1985; Chamas & Nokali, 2004; Gladwin, Margerison, & Walker, 1992; Gosman et al., 1977; Hites, Sekerak, & Sanders, 1999; Ingram et al., 1979; Kinzel, Charles, & John, 1981; Laghari, Suthar, & &Cygan, 1990; Nagel, 1975; Prigozy, 1989; Smith, 1976). Sometimes, virtual labs have replaced the use of hands-on laboratories (Gonzalez & Musa, 2005). Many research papers report a positive impact of computer simulations on students' learning (Adams, 1981; Campbell, 1985; Jimoyiannis & Komis, 2001; Kinzel et al., 1981; Laghari et al., 1990; Shute & Gawlick-Grendell, 1994; Tjaden & Dianne, 1995).

Gladwin et al. (1992) enumerate many advantages of computer simulations, such as coping with limited resources, the students' positive attitude towards using simulations and the increased impact of training at university on students' employment after graduation. Computer simulations can accommodate different learning styles, experiments can be repeated, offering an iterative learning opportunity, and students can use them outside class time for reflection and self-testing (Eckhoff, Eller, Watkins, & Hall, 2002). This is in correlation in particular with Kolb's (1984) experiential learning theory, which considers the construction of knowledge to take place in a cyclic manner. They promote a safe environment for students to test hypotheses and investigate outcomes of issues that sometimes are difficult or impossible to do with hands-on physical platforms, e.g. high voltage power plants (Hites et al., 1999; McAteer et al., 1996). Laghari et al. (1990) describe enhanced health and safety issues associated with using simulation software for electrical circuit design compared to hands-on high-voltage laboratories. Using the software has helped to reduce the exposure time to high voltages that the students and the instructor had to have.

Computer simulations allow students to perform sophisticated experiments virtually that otherwise would require a high physical or technical level. Experimentation can take place at the student's pace (Dobson, Hill, & Turner, 1995). Virtual labs are available any time (Dobson et al., 1995; McAteer et al., 1996). Teachers can save their contact time with the students by fostering the simulations (McAteer et al., 1996). They are fast, safe, clean and cost effective (Eckhoff et al., 2002; Gonzalez & Musa, 2005; McAteer et al., 1996). Distance learning courses can benefit from virtual labs (Blanchard et al., 2006; Eckhoff et al., 2002). On the other hand, there are also some disadvantages related to the use of computer simulations and virtual labs, which are detailed in the next subsection.

Hites et al. (1999) argue that even the best designed software cannot fully model the physical experiment, thus reducing the realism validity of the virtual lab. Magin and Kanapathipillai (2000) state that extensive use of simulations may result in engineering students not being able to recognize situations where mathematical models could result in significant errors that need empirical validation. The lack of instructor feedback is another disadvantage of virtual labs (Dobson et al., 1995). With virtual labs, there is a lack of operational and apparatus skills (McAteer et al., 1996). Despite the many advantages of computer simulations and virtual labs, there is a general agreement, either from the students' or the teachers' perspective, that simulations cannot and should not always replace the hands-on experience (Engum, Jeffries, & Fisher, 2003; Ma & Nickerson, 2006; Magin & Kanapathipillai, 2000; McAteer et al., 1996; Raineri, 2001; Ronen & Eliahu, 2000; Spicer & Stratford, 2001). Yet virtual labs can be effective assisting tools, whether offered online or as independent digital applications to be run on personal computers.

3. Remote (online) laboratories

The idea of implementing labs through the Internet for educational purposes can be traced back to the early 1990s, when Aburdene, Mastascusa, and Massengale (1991) suggested a futuristic solution for sharing laboratory equipment through the Internet. The early implementation trials took place in the United States. A remote control system operated robots distributed at four universities and NASA in the US (Kondraske et al., 1993). Since then, the number of Internet-based laboratories has rapidly increased year by year. The geographic distribution spread to Europe, Australia and East Asia.

One of the main advantages of online laboratories is the ability to share resources with other universities and hence reduce the economic cost of implementing and resourcing new experimental rigs (Eckhoff et al., 2002). The idea of sharing experimental resources for cost minimization can be traced to the early 1990s (Kondraske et al., 1993). This potential has been reported many times since then (Callaghan et al., 2008; Ma & Nickerson, 2006; Ogot, Elliot, & Glumac, 2002). In Australia, a project currently under development aims to share remote experiments on a nationwide scale (LabShare, 2010). Sharing remote experiments between universities enriches the students' experiential education (Ogot et al., 2002). The cost of new experimental rigs consumes a significant amount of the budget of higher education institutes, which has led to minimize laboratory work in the undergraduate curricula (Kirschner & Meester, 1988).

It has been reported in many papers that online laboratories have stimulated the students' enthusiasm towards the studied subject (Aktan et al., 1996; Ma & Nickerson, 2006). Online labs may accommodate different learning styles (Eckhoff et al., 2002). They can enhance the outreach of distance learning courses in engineering (Bourne, Harris, & Mayadas, 2005; Eckhoff et al., 2002; Ogot et al., 2002; Salzmann, Gillet, & Huguenin, 2000). Remote labs enable remote access to hazardous locations. Remote labs can facilitate social constructivism through sharing or performing experiments among students from different universities and countries. They offer flexibility in delivering laboratory experience. Remote labs provide *hands-on* experience via remote access to real equipments. Demonstrations can be created from the same experimental apparatus for K-12 education, where laboratory rigs are scarce (Ogot et al., 2002).

Despite the many advantages of remote labs, they also suffer from some disadvantages. Remote users are not fully exposed to the whole range of operational experience (Ogot et al., 2002; Srinivasagupta & Babu, 2003). It is stated that the absence of teachers, the isolation of students and the lack of detailed lab instructions in addition to the quality of the audio/visual feedback of the actual rig present the main disadvantages of remote labs (Kwon, Chiou, Rauniar, & Sosa, 2007). Developing remote access requires extra cost, which can be low or high depending on the nature of the experimental rig. Remote labs are more expensive to run than simulated labs, and they are affected by network performance and reliability. While many experiments can be automated to run fully remotely, many others still need human incorporation onsite, and some others are impossible to operate online. Remote experiments generally need a high bandwidth, which is not available in many developing countries, limiting their applicability where they are most needed.

4. Hands-on, simulated or remote?

In the literature regarding the effectiveness of one mode of laboratory over another, one can find a variety of different outcomes. For instance, conducting a hands-on lab remotely has been found less effective and more time consuming (Sicker, Lookabaugh, Santos & Barnes, 2005). On the other hand, other researchers reported that conducting hands-on experiments remotely is equivalent or slightly better than conducting them proximally (Corter et al., 2004; Lang et al., 2007). A virtual lab has been reported to equip students with equivalent skills to the corresponding hands-on lab (Engum, Jeffries, & Fisher, 2003). Spicer and Stratford (2001) did a qualitative study on the students' perception of replacing real field trips with simulated ones. The students showed a very positive attitude towards using the simulated field trip, but opposed the replacement of real field trips with simulated ones. They valued using the latter as a pre- or post-instrument to be utilized before or after the real field trip.

Blending a digital logic hands-on lab with a virtual lab has been found effective in enhancing the learning outcomes (Heise, 2006). Engum, Jeffries, & Fisher (2003) suggest that blending virtual and hands-on labs together may enhance the aimed outcomes of labs. After two years of combining computer simulations with hands-on lab activities in life sciences, McAteer et al. (1996) conclude that simulations have granted the students a better chance of conceptual understanding; however, there is still a need for the hands-on physical skills. Tzafestas, Palaiologou, and Alifragis (2006) designed an e-platform that combines a remote and simulated lab in one package to substitute a hands-on lab for distance learning purposes. They found that this platform could provide similar learning outcomes as the hands-on lab with regard to the mid- and high-level objectives of the laboratory. Lindsay and Good (2005) concludes that each mode (hands-on, virtual or remote) offer a different learning outcome and adapting hybrid access modes would enrich the learning experience of the students. Hofstein and Lunetta (2004) call for enhancing laboratory education by adopting further ICT. Ma and Nickerson (2006) emphasize the potential of all access modes of a laboratory for enriching laboratory education. There have been some trials involving embedding two modes together in the pedagogical process (Engum, Jeffries, & Fisher, 2003; Raineri, 2001; Tzafestas et al., 2006), with findings consistently indicating the advantages of hybrid structures. However, reports in the literature of hybrid labs that utilize hands-on, simulated and remote modes in one stand-alone complementary package are scarce.

5. The TriLab model; the triple access mode laboratory

Hands-on laboratories suffer from serious deficiencies that were discussed earlier. Blending the hands-on lab experience with virtual and/or remote lab experience could result in better constructivist learning. Hands-on labs generally require interfacing software for data acquisition and for hardware manipulation, a significant portion of modern laboratory rigs are run via computer controlled software (Ma & Nickerson, 2006). A second layer to this software that provides a simulated version of the hands-on experiment could be added resulting in a virtual lab. A third layer that provides a remote operation possibility (e.g. via the internet) could be added resulting in a remote lab. A hybrid triple mode model of laboratory education, so-called *TriLab*, is hence proposed in this paper. The TriLab could be defined as *a hybrid laboratory model that utilizes three different access modes of laboratory experience – virtual, hands-on and remote – combining them within a uniform software environment to enhance laboratory education in a pedagogically informed way*. The TriLab can facilitate enhanced pedagogies of experiential education such as introducing a novel application of Kolb's experiential learning theory for laboratory education (Abdulwahed & Nagy, 2009a) and the use of remote experiments in the classroom.

The TriLab model has been implemented for a modular and pilot-scale level control rigs at the Chemical Engineering Department of Loughborough University. The lab was designed in 2005 with the aim to support process control engineering education in undergraduate and postgraduate courses in the department. The lab has been mainly used in the second year course 'Instrumentation, Control and Industrial Practise'. In addition, it has been used in the first year course 'Process Balances' and in the postgraduate course 'Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems'. The lab contains six pilot-scale rigs and one modular rig manufactured by Armfield Ltd. The six rigs are used for process experiments of level control. The modular rig offers a level control

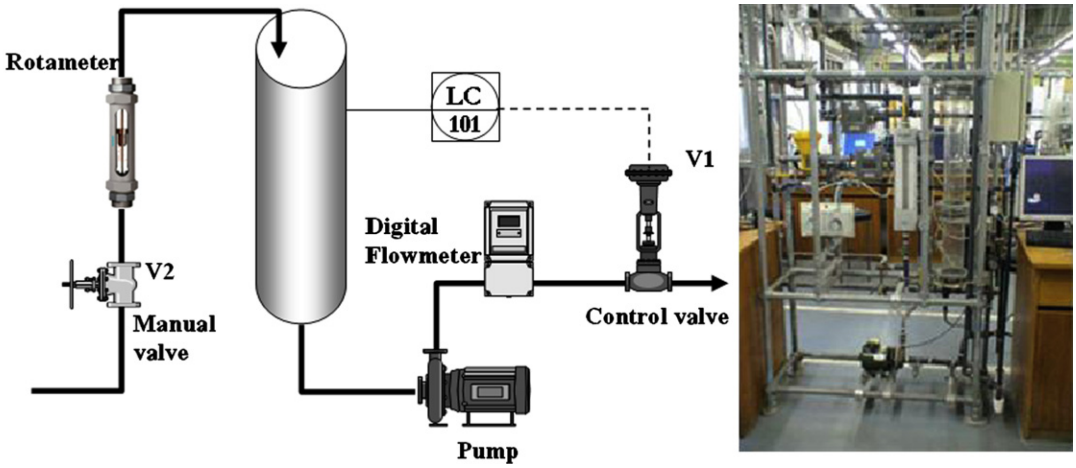

Fig. 1. Schematic diagram of the pilot-scale rig (left) and a picture of one of the experimental rigs (right).

experiment plus a number of other different process control demonstrations. The experimental procedures of the lab aim to introduce the 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 pilot-scale rigs were designed using authentic industrial equipments to provide the students with a more realistic view of industrial pilot-scale systems. The schematic diagram of the process and a picture of one of the pilot-scale rigs are shown in Fig. 1.

LabVIEW (Travis & Kring, 2007) was used to implement the virtual, hands-on and remote interface of the rigs in one software package. Joomla web content management system (LeBlanc, 2007) was used to implement the online portal of the remote lab (www.ilough-lab.com) leading to a fully integrated solution of implementing the TriLab (Abdulwahed & Nagy, 2009b). Fig. 2 shows the modular rig operating remotely through the iLough-Lab portal in a web browser.

6. The TriLab, an enabler of laboratory rigs reusability

Generally speaking, applying the TriLab concept to an experimental rig makes it more reusable. The TriLab makes a laboratory rig comparable to the Reusable Learning Object (RLO) metaphor, or (LO) for short. A learning object (LO) is a resource, usually digital and web-based, that can be used and re-used to support learning. A Learning Object is defined as “a computer mediated or delivered module or unit, which stands by itself that provides a meaningful learning experience in a planned learning context” (Ip, Young, & Morrison, 2002). Many laboratory rigs are multifunctional, offering different experiments for different courses. With a single functioning laboratory rig, different

Fig. 2. The Armfield modular rig operating remotely through an embedded VI inside the Joomla-based portal.

Table 1
Reusability example of the Loughborough process control lab after imposing the TriLab model; H = Hands-on, V = Virtual, R = Remote.

Year	Module	Academic year (2007–2008/ 2008–2009)		TriLab			Objectives
				H	*V*	*R*	
1	Process balances	Yes	Yes			Yes	Process dynamics
2	Instrumentation and control	Yes	Yes	Yes	Yes	Yes	PID control, calibration
3	Process control		Yes			Yes	PID tuning
MSc	Adv. Comp. Meth. for Modelling and Analysis of Chem. Eng. Sys.	Yes	Yes	Yes	Yes	Yes	PID control theory

aspects of the dedicated experiment can be exposed for audiences at different levels. An experiment offered remotely is inherently reusable, since it can be shared and adopted to show the application of theory in courses that are conducted at different universities. Hence, virtual or remote laboratory software is nothing else but a digital learning object that incorporates a physical rig.

Different components of the TriLab model of the Loughborough Process Control Lab have been used for courses in the first, second and third year undergraduate studies at the Chemical Engineering Department of Loughborough University. Also, the lab has been used in an MSc module in the Department. For instance, the remote component has been used to illustrate dynamic behaviours in the classroom in the Process Balances first year course. The three components (virtual, hands-on and remote) were used for the second year course Instrumentations, Control and Industrial Practise to demonstrate essential concepts of instrumentation (such as sensors and valves characteristics, calibration procedures) and PID control. The virtual lab was made available for the students to prepare, the hands-on lab was a compulsory part and remote experiments were conducted in the classroom. Remote experiments in the classroom were used to show PID tuning in the third year course Chemical Process Control. Hands-on PID control experiment and a post-lab session with virtual lab were applied in the MSc course Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems. The way that the TriLab model of the process control lab has been used represents an example of the high reusability potential of one experimental rig as a result of imposing the TriLab model; this is summarized in Table 1.

The TriLab model has enabled different aspects of the experiment to be used in different contexts and at different academic levels. The remote and virtual versions of the lab have allowed it to be utilized in an innovative and unconventional manner, empirical investigations were taken to measure the impact of different usages of the TriLab components on students' learning and attitudes.

Note that Table 1 represents how the different components of the TriLab have been utilized in different courses. Empirical investigations of the impact of the use of the components covered a number of utilizations, but not all. The focus of the empirical investigation with the undergraduate students has been on using the virtual component as an assistive tool for enhancing the hands-on laboratory outcomes following a standard control/experimental investigation procedure given that a good sample number was available in the second year course (around 65). The empirical investigation with the MSc course was mainly focused on the use of remote experiments in the classroom.

7. Empirical investigations of pedagogical applications of the TriLab

The virtual component of the TriLab has been used to help the students to prepare for the lab in a pre-lab session. The investigation of this approach has been done mainly with undergraduate students of the course 'Instrumentation, Control and Industrial Practise' and is achieved via comparing learning outcomes of control and experimental groups. The control group is composed of students who did not attend a pre-lab preparation session, while the experimental group is composed of students who attended the pre-lab preparation session. The investigation took place over two academic years and included mainly analysis of the marks of pre- and post-lab tests, lab report and final exam of the module. The pre- and post-lab tests were non-compulsory and the laboratory assessment was based solely on the lab report. The remote component of the TriLab has been used to demonstrate the application of taught theory in the classroom in real-time, e.g. bringing the lab into the classroom. The investigation of the approach has been done mainly with postgraduate students of the course 'Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems' and is achieved via surveying the students' opinion.

8. Investigations with the undergraduate students

8.1. Selection of the control and experimental groups in the undergraduate course

The number of registered students for the class was about 65 in average for the academic years 2007–2008 and 2008–2009. In the laboratory, six experimental rigs were used, with students working in groups of two or three. Students were divided into four groups, each consisting of 13–18 students. Each group used the lab rigs for two consecutive weeks to complete the experiments. The lab teaching spread over eight weeks from the second academic week, until the ninth academic week with group one scheduled for the first two weeks, group two for the third and fourth week, and so on. In the first academic week, an introductory lecture was organized in the classroom for all students, where the experiment was described. In this lecture, the laboratory was 'brought into the classroom' by using the remote laboratory mode, with the aim of stimulating the students' interest in the lab. A pre-lab preparation session was also organized for part of the groups, during which students came to the computer room and worked on the virtual laboratory software following the procedure from the lab manual, and working under minimal supervision. These pre-lab sessions (treatment) were applied to Groups 3 (G3) and 4 (G4), whereas Groups 1 (G1) and 2 (G2) had no treatment.

To guarantee equivalence as much as possible between the four groups, students were distributed evenly based on their percentage average in the previous academic year. The averages of the groups were G1 = 62.91%, G2 = 63.77%, G3 = 63.60% and G4 = 61.91% for the 2007–2008 academic year. For the 2008–2009 year, the averages were G1 = 66.81%, G2 = 66.46%, G3 = 66.99% and G4 = 67.12%. The groups

G1 and G2 represented the control group, and students of G3 and G4, who attended the preparation sessions with the virtual lab, formed the experimental group.

About 60–70% of the students of G3 and G4 responded to the request to attend the preparation session each time. The previous year average of the experimental group students was 65.71% in the 2007–2008 academic year. Students from Groups 1 and 2 formed the control group with a group average of 63.34%. For the 2008–2009 academic year, the experimental group students' average was 68.45% vs. 66.63% average of the control group students. The Mann Whitney *U* test of the difference in the previous year average between the students of the control and the experimental groups revealed a statistically non-significant value (p-value $= 0.298 > 0.05$ for the 2007–2008 academic year and p-value $= 0.51 > 0.05$ for the 2008–2009 academic year), indicating that the control and the experimental groups are similar in regard with the previous year academic achievement. The empirical investigation for the 2007–2008 academic year has been similar to the one in the 2008–2009 academic year. The main aim of conducting the same investigation was to maximize the sample number, robust findings in educational research requires a reasonably good sample number (Cohen, Manion, & Morrison, 2005).

8.2. Measurement' instruments

8.2.1. Laboratory report

All students had to submit a compulsory comprehensive lab report within two weeks of the end of the second laboratory session. The lab report was prepared in teams of 2–3 students who worked on the same rig during the lab sessions. The body of the report is no more than 20 pages. The students were required to include key figures, tables and calculations in the main body of the report. The lab report is structured into the following sections: 1- Summary; 2- Table of Content; 3- Introduction; 4- Theory; 5- Experimental Procedure; 6- Results and Discussion; 7- Conclusions; 8- References; and 9- Appendices. Further details of the lab report structure are provided in the next subsection. Marking was based on how well the report was organized in the light of the given structure, the correctness of the diagrams, the rationale of the data analysis and discussion, correctness of the figures and formatting, and the summary match with the experimental observations and conclusions alongside the report. The laboratory reports of all the students of both academic years were marked by the course lecturer. Since the report was written as a team effort, the marks given to individual members of the team were identical.

8.2.2. Pre- and post-lab tests

The students were asked to take pre- and post-lab test on a voluntary basis. The pre- and post-lab tests were given to students in Week 1 and Week 2. The pre-lab tests were designed mainly to measure the students' preparation level before the lab, while the post-lab tests were designed to measure the students' learning outcome after the lab sessions. The tests were designed in correlation with the laboratory objectives and in discussion with the course lecturer. The tests have been taken in the first and last 15 min of the lab session. All tests were marked by the same person for both academic years 2007–2008 and 2008–2009.

In addition to the lab report and the pre- and post-lab tests, the module exam results and a survey of students' opinions are used for data analysis of the impact of the using the virtual component of the TriLab on the undergraduate students.

In the academic year 2006–2007, students were also divided into four groups G1, G2, G3 and G4 that are spread over the semester. However no virtual lab, preparation sessions, pre- and post-lab tests, were available to any of the groups resulting in an equivalent treatment. Data of students learning outcomes of the hands-on laboratory were used for comparison with consequent years as will be detailed in the data analysis section. Table 2 shows details the type and timing of the activities for all students corresponding to the three academic years.

8.3. Data analysis

For further in-depth investigation the marks of the laboratory report of the students of the 2006–2007 academic year (before this project started) were analysed. These students will be called 'Y0 students', while the terms 'Y1 students' and 'Y2 students' will refer to the students of the academic years 2007–2008 and 2008–2009, respectively. All the hypothesis tests in this section were achieved using the Mann-Whitney *U* test.

Y0 students were allocated similarly to four groups over eight weeks of the autumn semester. There were 20 students in G1 and G2 (control) and 25 students in G3 and G4 (experimental). In checking the previous year averages, the mean of the control group was 63.49% vs. 63.52% for the experimental group, with a p-value $= 0.79 > 0.05$ indicating identical allocation. The students of all groups conducted the lab work similarly; there were no preparation sessions or pre- and post-lab tests. However, the control group students obtained higher means in the laboratory report than the experimental group students, with a statistically significant difference (64.70% for control vs. 59.24% for experimental, p-value $= 0.012 < 0.05$). *This finding indicates that the progress of the semester impacts negatively on the students learning*

Table 2
Involvement of the groups of the second year course in the empirical measurements over the three academic years (2006–2007, 2007–2008, and 2008–2009). G1 and G2 have conducted the hands-on lab during the first half of the semester while G3 and G4 have conducted the hands-on lab during the second half of the semester.

		G1	G2	G3	G4
2006–2007	Lab preparation sessions	No	No	No	No
	Pre- and Post-lab tests	No	No	No	No
	Lab report	Yes	Yes	Yes	Yes
2007–2008	Lab preparation sessions	No	No	Yes[a]	Yes[a]
	Pre- and Post-lab tests	No	No	Yes	Yes
	Lab report	Yes	Yes	Yes	Yes
2008–2009	Lab preparation sessions	No	No	Yes[a]	Yes[a]
	Pre- and Post-lab tests	No	No	Yes	Yes
	Lab report	Yes	Yes	Yes	Yes

[a] indicates partial response to the attendance of the preparation sessions.

outcomes of the laboratory sessions. This can be explained by the fact that in the second half of the semester, students have a higher study and cognitive load, as the course becomes more complex and the assignments and coursework load increases.

The statistical analysis of the laboratory report of the Y1 & Y2 students of the control and experimental groups revealed higher means with a statistically significant p-value for the experimental group students vs. the control group students; the statistics are 67.28% mean of the Y1 & Y2 experimental ($N = 46$) vs. 63.06% mean for Y1 & Y2 control ($N = 65$), with p-value $= 0.002 < 0.05$. *This is opposite to the performance of the Y0 students*. Fig. 3 shows the laboratory report marks as the semester progresses. Further statistical analysis of the performance of the control group of Y0 students vs. the control groups of the Y1 & Y2 students was conducted to check whether the student cohorts are identical. The results revealed close means with no statistical significance indicating that the student cohort is rather similar (64.70% for Y0 control vs. 63.06% for Y1 & Y2 control, p-value $= 0.536 > 0.05$). Furthermore, the check of the previous year's performance of the students of the control group of Y0 vs. Y1 & Y2 control groups students revealed close averages and no statistical significance (63.55% for Y0 control vs. 63.49% for Y1 & Y2 control, p-value $= 0.873 > 0.05$).

To check whether the lab report mark of the students of the experimental groups of Y1 and Y2 are higher with a statistically significant value than their peers of Y0 (G3 and G4 students), the Mann–Whitney U test was performed. The analysis revealed a statistically significant difference in the means with a very small p-value (67.28% for Y1 & Y2 experimental vs. 59.24% for Y0 experimental, p-value $= 0.000 < 0.05$). The previous year averages were almost identical, with no statistically significant indication of difference (65.12% for Y1 & Y2 experimental vs. 63.51% for Y0 experimental, p-value $= 0.430 > 0.05$). Table 3 provides a summary of all these statistics.

The analysis of the laboratory marks of the students revealed several conclusions. Firstly, *the students who have had prepared for the lab using the virtual version have provided higher quality reports than their peers of the same year (students of the control groups of Y1 & Y2)*. Secondly, *those students have also coped better with the increased complexity, greater coursework and cognitive load alongside the semester progress with regard to performance in the Process Control Lab, reflected by their laboratory report marks*.

The analysis of the pre- and post-lab tests has revealed statistical significance in all four tests (pre- and post-lab tests of Week 1 and pre- and post-lab tests of Week 2). In the pre-lab tests of laboratory Week 1, the control group students' average was 47.22% (SD $= 20.84$, $N = 56$), while the experimental group students' average was 66.80% ($N = 35$, p-value $= 0.000 < 0.05$). In the pre-lab tests of Week 2 the control group students' average was 28.55% ($N = 59$), while the experimental group students' average was 43.04% ($N = 35$, p-value $= 0.000 < 0.05$). In the post-lab tests of Week 1, the control group students' average was 44.08% (SD $= 19.21$, $N = 58$), while the experimental group students' average was 60.07% ($N = 36$, p-value $= 0.000 < 0.05$). In the post-lab tests of Week 2, the control group students' average was 41.84% ($N = 57$), while the experimental group students' average was 58.37% ($N = 30$, p-value $= 0.001 < 0.05$). For the mark of the final exam of the module, the control group students' average was 48.40% ($N = 65$), while the experimental group students' average was 58.47% ($N = 46$, p-value $= 0.018 < 0.05$).

The exam marks were analysed to investigate whether there is a statistically significant difference between the students of the control and experimental groups of Y1 and Y2.

The exam questions of both years were constructed by the course lecturer, who was also responsible for marking all answers. The mean average of the exam mark of the students of the control groups was 48.40% vs. 58.47% for the students of the experimental groups, with a p-value $= 0.018$, *indicating statistically significant enhancement of about 20% in the students' performance in the exams due to better activation of the dimensions of Kolb's cycle of the laboratory component of the module*. Fig. 4 shows the six measures (4 lab tests, report mark and module exam mark) of the control and experimental groups, while a summary of the statistics is shown in Table 4.

The way the virtual component of the TriLab model was applied included one major iterative learning phase through the pre-lab preparation session. However, this single opportunity of cyclic learning has significantly enhanced the students' learning outcomes.

The new approach of conducting the Process Control Lab introduced additional components compared to the classically taught labs, such as the virtual lab, the preparation session and the pre- and post-lab tests. The students of the 2007–2008 academic year were asked to rate the usefulness of the different components on a scale from 1 to 6, where '1 = Not useful at all', '2 = Very little useful', '3 = A little useful', '4 = Probably useful', '5 = Quite useful' and '6 = Very much useful'. Students were similarly surveyed for their opinion of conducting post-lab experimentation with the remote component.

The analysis of the responses shows a statistically significant difference between the control ($N = 20$) and the experimental ($N = 12$) group students in their opinion towards of the usefulness of the virtual lab, with a p-value $= 0.032 < 0.05$, and means of control/experimental $= 4.15/5.00$ on a scale of 6. Both groups showed a positive opinion; however, the experimental group students appreciated the virtual lab more, very likely because they used it more than the control group students. The experimental group students show a more positive attitude towards the pre-lab tests than the control group students; the means of the control/experimental $= 3.10/3.83$ with p-value $= 0.091$. Considering the small sample number ($N = 20$/Control, $N = 12$/Experimental), this p-value is less than 0.1 and could be admitted as an indication of a statistically significant indicator (Cohen et al., 2005).

The higher appreciation of the pre-lab test by the experimental group students could be related to the fact that they came more prepared and that the pre-lab tests helped them to contextualize their preparation. This finding is consistent with the qualitative observation of the greater interest of the experimental group to answer the tests, which was noted by both the course lecturer and the lab teaching assistant.

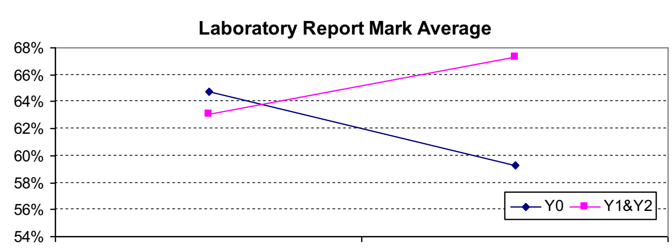

Fig. 3. The laboratory report mark average of Y0 and Y1 & Y2 students as a function of the semester progress. (G1 and G2 have conducted the lab in the first half of the semester, while G3 and G4 have conducted the lab in the second half of the semester).

Table 3
Statistics of the students' perception of the new components of the lab.

Variable	Asymptotic significance (the *p*-value) of the Mann–Whitney *U* test	Sample number (con./exp.)	Means % (con./exp.)
Previous year average: Y0 control vs. Y0 experimental	0.790	20/25	63.49/63.52
Laboratory report mark: Y0 control vs. Y0 experimental	0.012	20/25	64.70/59.24
Laboratory report mark: Y1 & Y2 control vs. Y1 & Y2 experimental	0.002	65/46	63.03/67.28
Laboratory report mark: Y0 control vs. Y1 & Y2 control	0.536	20/65	64.70/63.06
Previous year average: Y0 control vs. Y1 & Y2 control	0.873	19/63	63.55/63.49
Laboratory report mark: Y0 experimental vs. Y1 & Y2 experimental	0.000	25/46	59.24/67.28
Previous year average: Y0 experimental vs. Y1 & Y2 experimental	0.430	22/44	63.52/65.12

Regarding the usefulness of the preparation session, the post-lab test and the experiments in the classroom, the students of both groups showed a somewhat positive attitude, with no statistically significant difference. Nevertheless, the experimental group responses were slightly more positive on all aspects. A summary of the statistics is shown in Table 5.

The students of both groups had a more positive attitude towards the post-lab test in comparison with the pre-lab test. The Wilcoxon test of difference in the control group students' attitude towards the pre- and post-lab tests revealed a p-value $= 0.053 < 0.1$ ($N = 12$), indicating a statistically significant difference, while it returns a p-value $= 0.257 > 0.1$, for the experimental group students ($N = 11$), indicating no statistically significant difference. A potential explanation is that the control group students found the post-lab tests more meaningful than the pre-lab tests, because the former tested them for knowledge they had already experienced.

With regard to the students' opinion of post-lab experimentation with the remote component, the average for the control group is 4.30/6, while the average for the experimental group is 5.27/6, p-value $= 0.044 < 0.05$. Both groups had a positive attitude towards conducting post-lab experimentation remotely; however there is a statistically significant difference, with a higher attitude of the experimental group students. *This demonstrates that preparation for the lab with a virtual version has a statistically significant impact on motivating students towards further inquiry and experimentation, therefore providing a better constructivist experience for laboratory education.*

9. Investigations with the postgraduate students

The remote component of the TriLab has been used mainly for demonstrating theory in the classroom. This method has been applied to postgraduate students and along three years, 2007, 2008, and 2009. The number of the registered students in the MSc course is between 10 and 13.

9.1. The procedure of remote experimentation in the postgraduate classroom

In 2007, a pilot experiment of using remote labs in the lecture was conducted. A remote connection to the Cambridge WebLab (Selmer, Kraft, Moros, & Colton, 2007) was achieved and a demonstration of 15 min duration was given during a theoretical PID control lecture. A positive impact on the students was generally noticed; however the time was rather short. In surveying the students' opinion, 77.8% of the students found it 'Good' to explain theory with remote experiments, and 55% reported that the demonstration time was short. Hence, it was decided to dedicate more time for the remote experiments in the classroom.

In 2008 and 2009 courses, the demonstration was conducted for 50 min following a theory lecture on PID control. More time was allocated for the students to discuss the influence of different tuning parameters. For both years, the students showed high attention to the lecture. They were interested in trying and testing the theory themselves in the classroom using the remote experiment. They applied their suggestions in real time and looked at the outcome. Interesting discussions evolved amongst the students in this lecture of what the best P,

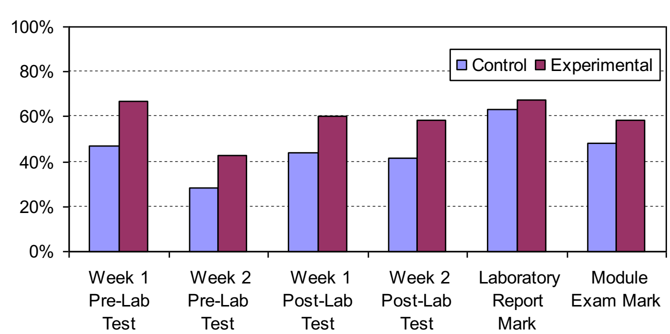

Fig. 4. Individual means of the questions of the post-lab test of the Week 2 laboratory session of the 2008–2009 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

Table 4
Summary of the statistics of measures of the Process Control Lab learning outcomes detailed in Chapter 6. The fields ‘Sample Number’, ‘Mean’ and ‘SD’ present the data for the control/experimental groups respectively.

Instrument	Sample Number	Mean	*p*-value
Pre-lab test of Week 1	56/35	47.2/66.8	0.000
Pre-lab test of Week 2	59/35	28.6/43.1	0.000
Post-lab test of Week 1	58/36	44.1/60.1	0.000
Post-lab test of Week 2	57/30	41.8/58.4	0.001
Laboratory report mark	65/46	63.0/67.3	0.002
Final exam mark	65/46	48.4/58.5	0.018

PI or PID control structures are based on their real observations. The remote experience itself was stimulating for the students, and the dynamics of the class changed remarkably in both years after the remote experiments were introduced. Fig. 5 shows the remote experimentation in the MSc lectures of the 2009 year.

In both years, the audience response system (ARS) was used (TurningPoint, 2009) to enhance the interactivity of the lecture. The students had to answer multiple-choice questions in relation with the taught theory or the remote experiments. Their answers are collected and presented through the ARS hardware and software. A quantitative representation shows up immediately after the students have answered. The voting system has been used in other lectures, too, during the module. Table 6 shows a summary of the usage of the remote experiments in the MSc classroom.

A number of research questions (RQ) have been investigated by surveying the students opinions towards the new approach. These are detailed in the following subsections.

9.2. RQ1: the impact of a blended lecture vs. a theory lecture

The demonstrations in the postgraduate courses in 2008 and 2009 were used to obtain a pedagogical measurement of whether blending classical theoretical lectures with real experimentation has an impact on the following factors: conceptual understanding, enjoyment, the motivating role towards an engineering career, and the motivating role towards studying further theory. To measure the difference between blended lectures and purely theoretical lectures, questionnaires were designed to obtain the students’ opinion. The students had to rate their opinion on whether a blended lecture is better than a pure theory lecture on a scale of 1–5 for each of the previous four factors, where ‘1 = Much Less’, ‘2 = Less’. ‘3 = The Same’, ‘4 = More’ and ‘5 = Much More’.

Questionnaires were collected after the module oral exam; there were 11 respondents in total for 2008 and 9 respondents for 2009. The statistics of the students’ responses for 2008 and 2009 are shown in Table 7. The results show a positive opinion of the students of the blended lecture.

For instance, 81.8% of the 2008 students considered the blended lecture ‘More’ or ‘Much More’ enjoyable (89.9% for 2009). For the ‘Conceptual understanding’ variable, 100% of the students in both years considered the blended lecture ‘More’ or ‘Much More’ helpful than the purely theoretical lecture. Also, 100% of both years’ students considered the blended lecture ‘More’ or ‘Much More’ motivating towards an engineering career than the purely theoretical lecture. 90.9% of the 2008 students expressed the opinion that the blended lecture was ‘More’ or ‘Much More’ motivating for studying further theory than the purely theoretical lecture (88.9% for 2009).

Hence, *it can be inferred that the remote experiment in the classroom left a positive impact on the students with regard to the following factors: ‘Enjoyment’, ‘Conceptual understanding’, ‘Motivation towards an engineering career’ and ‘Motivation towards studying more theory’* when compared to the purely theoretical lectures.

Therefore, it is recommended theory lectures to be combined with authentic experimentation when possible to enhance students’ attitude towards the lecture and increase their motivation.

9.3. RQ2: the impact of remote experiments in the classroom on PID control theory understanding

This research question aimed to investigate the students’ opinion of to what extent and why the remote experiments in the classroom helped them to understand the related theory, and also what their opinion is of exploiting remote experiments in the classroom with other courses. The measurements were taken with the MSc students of the years 2008 and 2009 through questionnaires. The ‘What’ question was a closed one rated on a scale of 6 (1 = ‘It confused me more’; 2 = ‘Did not help at all’; 3 = ‘A little bit helpful’; 4 = ‘Probably yes’; 5 = ‘Quite much helpful’; and 6 = ‘Definitely helpful’), while the ‘Why’ question was open ended. The findings are reported by means of descriptive statistics and the qualitative responses of the students. The results show the positive opinion of the students. They believe that the remote

Table 5
Statistics of the students’ perception of the new components of the lab.

Variable	Exact Significance, Mann–Whitney *U* test (the *p*-value)	Sample Number (Con./Exp.)	Means (Con./Exp.)
The Virtual Lab	0.032	20/12	4.15/5.00
The Pre-Lab Test	0.091	20/12	3.10/3.83
The Post-Lab Test	0.604	20/12	3.90/4.08
The Pre-Lab Preparation Session	0.197	10/11	4.00/4.73
Lab Experiments in the Lecture	0.412	20/12	4.32/4.58
Post-Lab Experimentation with Remote Labs	0.044	20/11	4.30/5.27

Fig. 5. Remote experiments during the postgraduate lectures of the 2009 course – students looking at the results of the PID control of the remote experiments using the Loughborough Process Control Lab.

experiment in the classroom helped them to understand PID control theory. The majority of the students (72.8% for 2008 and 77.8% for 2009) reported that the remote experimentation was quite or definitely helpful as shown in Fig. 6.

For the open–ended part of the question (why is it helpful?), eight (out of twenty) students provided a response; these responses are:

Student 1: "*It helps to understand the theory by seeing the process in operation.*"
Student 2: "*We got to see the theory into practise*."
Student 3: "*Because it offers a practical approach to learning.*"
Student 4: "*We got the opportunity to practise the experiments and to compare our results with what we were taught during the lecture*."
Student 5: "*We knew fundamental things of PID, but it helped to understand practically. Also it helped to understand various PID effects on the system*."
Student 6: "*It helped in showing the practise and to play with various Kc, Td and Ti values while noting controller action*."
Student 7: "*Remote experiments helps to see what actually happens in the system and why. It motivates you more to study the subject*."
Student 8: "*Helped in understanding the development in technology*."

The common theme that emerges from the students' comments is that showing the PID theory in practice plays a main role in helping the students to understand the theory.

In another question in the survey, the students were asked whether they would like to have remote experiments in other courses to demonstrate the theory. All students from 2008 to 2009 have agreed with exploiting remote experiments in other courses to demonstrate the taught theory, and none reported disagreement.

These results show the positive impact of conducting remote experiments in the classroom on the students' grasp of PID control theory, and also shows that would like to see this practice introduced to other courses.

9.4. RQ3: the impact of using different remote experimental rigs on students' opinion

This research question aimed to investigate whether exploiting different experimental rigs remotely in the classroom has a different impact on the students or not. The Cambridge WebLab rig (Selmer et al., 2007) was exploited remotely in one lecture in 2008, while the Loughborough Process Control Lab (iLough-Lab, 2009) was exploited for the 2009 course. Both remote experimentation lectures took a very similar format. They were given one day after the theory lecture and lasted for 1 h. To find whether there is a statistically significant difference between the two years' surveys, the Mann–Whitney U test was used. The test outcome did not reveal any statistically significant difference between the responses of the 2008 students and the responses of the 2009 students, as shown in Table 8.

The students of both years seemed to agree equally on the role of remote experimentation on enhancing the lecture's impact on enjoyment (RQ3.1), conceptual understanding (RQ3.2), motivation towards an engineering career (RQ3.3) and motivation towards studying further theory (RQ3.4). The students also equally believed in the applicability of remote control operations in industrial settings (RQ3.5). The students of both years thought equally of the positive impact of the remote experimentation on their understanding of PID control theory (RQ3.6) and equally thought that remote experiments should be exploited in other courses to enhance theory understanding (RQ3.7).

These findings may indicate that sharing remote experiments among institutions can be fruitful and could result in similar beneficial outcomes.

Table 6
The usage of remote experiments in the MSc classroom.

Year	Module	Student' number	Time	Used lab	Used for	With ARS
2007	CGP075	10	15 min	Cambridge WebLab	Pilot trial illustrating PID Control	No
2008	CGP075	11	50 min	Cambridge WebLab	Detailed illustration of PID Control	Yes
2009	CGP075	13	50 min	iLough-Lab	Detailed illustration of PID Control	Yes

Table 7
Statistics of the students' response of the impact of the blended lecture with experimentation approach vs. the classical lecture. Values are in percentage % and represents the 2008/2009 surveys respectively.

	Much less	Less	The same	More	Much more
Enjoyment	0/0	0/0	18.2/11.1	36.4/33.3	45.4/55.6
Conceptual understanding	0/0	0/0	0/0	63.6/33.3	36.4/66.7
Motivation towards an engineering career	0/0	0/0	0/0	54.5/33.3	45.5/66.7
Studying more theory about the Presented material	0/0	0/0	9.1/11.1	45.5/33.3	45.5/55.6

10. Discussion

Using the virtual lab in a preparation session in the undergraduate course has remarkably enhanced the learning outcomes of the students, this positive impact can be explained from many perspectives. According to the dual coding theory of information cognition, the human mind perceives and stores verbal and visual information through two distinct channels (Clark & Paivio, 1991). The implication on educational processes is that incorporating visual objects with a written text (e.g. the lab manual) can lead to better learning (Slavin, 2005). The virtual lab presents a suitable tool to visualize the experimental rig in a simplified way to show the experimental data in plots.

The VARK learning styles model suggests that there are four main learning styles: Visual, Aural, Read/write and kinaesthetic (Fleming & Mills, 1992). Preparing from the lab manual could be suitable for those students who have a strong read/write learning style. However, combining the virtual lab with the lab manual in the preparation accommodates those students who have visual and kinaesthetic learning styles. This is because the virtual lab visualizes the experiment (visual style) and gives the students a chance to conduct the experiment virtually (kinaesthetic). The learning pyramid model (Weenk, 1999) suggests that information retention rates are different depending on the learning method (5% lecture, 10% reading, 20% audio/visual, 30% demonstration, 50% discussion group, 75% practise by doing, 90% teaching others). The virtual lab provides the chance to do the experiment and hence results in a much higher knowledge retention rate than using the lab manual alone. Offering the students a pre-lab session, by which they prepare using the lab manual and the virtual lab, may assist in overcoming some of the shortcomings of hands-on labs such as cognitive overload and limited exposure to the experimental rig.

According to Kolb (1984), higher order learning occurs in a constructivist cyclic manner that is composed of four distinct phases: Concrete Experience, Reflective Observation, Abstract Conceptualization and Active Experimentation. The use of the virtual lab in a preparation session is a way of activating Kolb's cycle, hence producing higher order learning. The use of the virtual lab has enabled activating a student-centred constructivist process. Such processes normally carries out reasonable elements of observations, reflection, feedback and construction of knowledge compared to classical one-go methods of teaching and learning, e.g. conducting a hands-on lab in a single demonstration. It is shown mathematically that the student-centred approach is enabler of enhanced learning outcomes (Abdulwahed, Nagy, & Blanchard, 2008).

The positive impact of demonstrating authentic experiments of PID control theory in the classroom can be related to the mathematical nature of the topic, which can be too abstract for chemical engineering students when not connected to real examples. Supplementing theory with real experimentation justifies the taught mathematics and transforms the abstract concepts into a lively experience. In this particular case of teaching PID control, the experiments show the mechanisms through which the controller's mathematical algorithm responds to the deviations of the output from the setpoint. This associates the students' abstract cognition of the mathematical equations with additional visual/kinaesthetic cognitive axes; hence, the students receive information through two channels instead of one. The dual coding theory argues that enhanced cognition occurs in such cases (Clark & Paivio, 1991). It is also probable that engineering students are more accustomed to visual and kinaesthetic cognition than to abstract cognition, hence the interpretation that they find such an approach more enjoyable and understandable.

Interactive lectures that involve experimentation are more suitable to the engineering students' learning style. The learning style of engineering students tends to be a mix of abstraction and experimentation (Kolb, 1984). This finding has been reported in David, Wyrick, and Hilsen (2002) and Stice (1987). Hence, a pure theory lecture is not consistent with engineering students' learning style, while the blend of theory and experimentation is more compatible. In accordance with VARK learning style model (Fleming & Mills, 1992), the interactive lecture can accommodate visual and kinaesthetic learning style students in addition to read/write students, whereas the classical lecture is mainly read/write oriented with little visual content. The interactive lecture included visual aids, demonstrations, and also time for discussion amongst the students about the experiments, which is seldom applied in classical theoretical lectures.

Frustration caused by lack of understanding in the theory lecture plays a role in demotivating the students towards the taught subject, which impacts negatively on their future career. When students understand theory in association with remote experimentation, they interact constructively with each other, and furthermore they try to apply the theory themselves simultaneously. This leads to demolishing

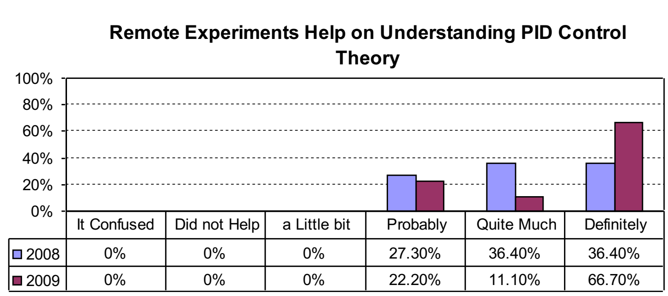

Fig. 6. Statistics of the students' response about the impact of PID control experiments in the classroom on PID theory understanding and their opinion of embedding classroom experiments in other courses.

Table 8
Statistics of significant difference of the impact of using Cambridge WebLab vs. using the iLough-lab in the classroom. Sample number is 11/9 (2008/2009).

Research Question	Asymptotic Significance (p-value) of the Mann–Whitney U test	Means (2008/2009)
RQ3.1	0.656	4.27/4.44[a]
RQ3.2	0.261	4.36/4.67[a]
RQ3.3	0.456	4.45/4.67[a]
RQ3.4	0.766	4.36/4.44[a]
RQ3.5	0.395	5.27/5.25[b]
RQ3.6	0.370	5.09/5.44[b]
RQ3.7	0.941	5.27/5.22[b]

[a] Scale from 1 to 5 where 5 is the highest preference.
[b] Scale from 1 to 6 where 6 is the highest preference.

the frustration and increasing the motivation of the students. The measurements of the students' attitude towards the combined theory and authentic experimentation support this argument.

The TriLab model opens doors for a number of research questions. For instance, what is the optimal methodology of combining the three components together in one integrated laboratory learning unit. Initial proposal suggests that the series ($V \rightarrow H \rightarrow R$) in which the hands-on lab is preceded with a virtual preparation session and following it with a remote lab activity could foster cyclic learning (Abdulwahed & Nagy, 2009a). However, other alternatives such as ($R \rightarrow H \rightarrow V$) or ($H \rightarrow R \rightarrow V$), etc. could also be investigated.

11. Conclusions

The important role of the laboratory in engineering and science education has been frequently emphasized in the literature. The classical and most widespread form of conducting laboratory education is the hands-on mode. Recent advances in ICT have led to the development of two new modes: the virtual (simulated) and the remotely operated labs. The literature review of virtual, hands-on and simulated labs has been provided with details of the advantages and disadvantages of each mode. It has also been demonstrated that the literature does not show consistently that one mode is superior to the others. One common conclusion found in the literature is the need to use hybrid structures. Despite the fact that hands-on laboratories are still central, combining the other modes with the hands-on lab in one model and applying them in a complementary way could result in better learning outcomes. This approach has been applied to the Loughborough Process Control Lab in the Chemical Engineering Department of Loughborough University. A triple access mode laboratory model, namely the TriLab, was developed with LabVIEW and Joomla. The virtual and remote components of the TriLab were used to enhance the laboratory pedagogy and to assist understanding classroom theory. Empirical study of the new approach effectiveness was taken over three years with undergraduate and postgraduate students. The findings showed clearly the positive impact of applying the TriLab components into the teaching and learning on students learning outcomes and motivation.

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