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**TOWARDS ENHANCING LABORATORY
EDUCATION BY THE DEVELOPMENT AND
EVALUATION OF THE “TriLAB” – A TRIPLE
ACCESS MODE (VIRTUAL, HANDS-ON AND
REMOTE) LABORATORY**

By

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Abstract

This thesis contributes to the general body of knowledge of research into engineering education. The main scope of the thesis is on enhancing laboratory education. There are three main types of laboratory: virtual, hands-on and remote. The hands-on lab is the oldest and most commonly used medium for experiential education in undergraduate degrees of science and engineering. The literature review of laboratory education has shown that hands-on labs suffer from many disadvantages, which can be overcome by utilizing hybrid laboratory structures that incorporate virtual and/or remote modes.

The investigation into enhanced laboratory education is achieved via implementing new technical and pedagogical models of conducting laboratories. The technical model incorporates three access modes (virtual, hands-on and remote) to the laboratory experience in one software package called the TriLab. The TriLab concept has been applied to the Process Control Lab at the Chemical Engineering Department of Loughborough University and has been implemented using LabVIEW. The Joomla web content management system was used to develop an online portal for disseminating the remote component of the TriLab resulting in the first remote lab portal of Loughborough University and one of the few available in the UK.

A pedagogical model of laboratory education based on Kolb's experiential learning theory and by the utilization of the TriLab concept is proposed. The model is built on a hypothesis, which states that the poor learning outcomes of hands-on laboratory sessions can be associated with poor activation of the stages of Kolb's experiential learning cycle. It has been proposed that access to a virtual lab in a preparatory session will play a role in activating the stages of Kolb's cycle. To verify this, educational experimentation procedures were designed and applied to two groups, control and experimental. Measurements via pre- and post-lab tests, marks for the laboratory report and the final exam of the module have been performed. The statistical analysis of the measurements has supported the stated hypothesis and solution proposal. The proposed pedagogical model is one of the few that provide a way of conducting laboratory education based on constructivist educational theories. The remote component of the TriLab was used in the classroom to explain the application of theory into

practice. The students' opinion has shown a very positive attitude towards the approach. Explanations of the findings were achieved in the light of pedagogical and cognitive psychology theories.

The literature review of pedagogy shows that many pedagogical research areas (e.g. feedback and formative assessment, self-regulated learning and instructional design) share common concepts with engineering, in particular with feedback control systems engineering. This correlation has been highlighted and developed further, where mathematical models based on feedback control systems methods are proposed to capture the dynamics of educational processes by means of quantitative tools. In particular, open- and closed-loop learning models are developed and analysed. The literature review of educational feedback research shows quantitative results that are in correlation with the predictions of the developed models. Finally, the concept of 'Systems Pedagogy' as a field of ENGINEERING the education has been proposed. This is probably the first time that control systems engineering methods have been used to model pedagogical processes.

This PhD work is highly interdisciplinary and included elements of LabVIEW programming, online portal design and development, educational experimentation design, development of instruments for educational measurements (questionnaires, tests, quizzes), the use of descriptive and inferential statistics for data analysis, review of pedagogical theories, reviews on laboratories and development of the control systems models of educational processes. These are detailed throughout the thesis chapters. The developments and findings have been published in peer-reviewed journals and demonstrated at many international conferences.

Keywords: Constructivism, Laboratory Education, Open- and Closed-Loop Learning, Pedagogy, Systems Pedagogy, the TriLab.

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Chapter 1.

INTRODUCTION OF THE THESIS

Overview

A general overview of the thesis is provided in this chapter. Since that this thesis contributes to the literature on engineering education, a short introduction to engineering education research is provided. This is followed by outlining the scope of the thesis, which is regarding laboratory education. A brief overview of the research gap in the field and the aims of the thesis are then presented. This is followed by a section introducing the methodologies that have been used and the way that the research has been tackled. Subsequently, a section on the general structure of the thesis and the content of the individual chapters is given. The PhD project main outcomes are introduced, followed by a section on the difficulties and constraints of the project and the chapter's conclusions.

1.1 Introduction to Engineering Education

This thesis contributes to the literature on engineering education research. Engineering education research is inherently multidisciplinary, crossing over different fields (Streveler and Sminth, 2006; Beddoes et al., 2009). In particular, pedagogy and social science research methods are relevant in forming engineering education research, as shown in Figure 1.1. Engineering education research is an emerging field of science that is still in the process of rigor establishment (Streveler and Smith, 2006). It is argued that engineering education has not yet developed into a distinct discipline (Borrego, 2007). Wankat et al. (2002) describe researching the innovative practices in engineering education until the mid 1980s with the adage “We tried it and liked it and so did the students”. Engineering education research is rather limited in quantity and quality because of many factors. For instance, conducting rigorous engineering education research requires knowledge of theories and research methods that reside out of the engineering domain (Wankat et al., 2002). Furthermore, engineering educators are mainly assessed in their career based on their disciplinary research and very little reward, if any, is given for excellence or

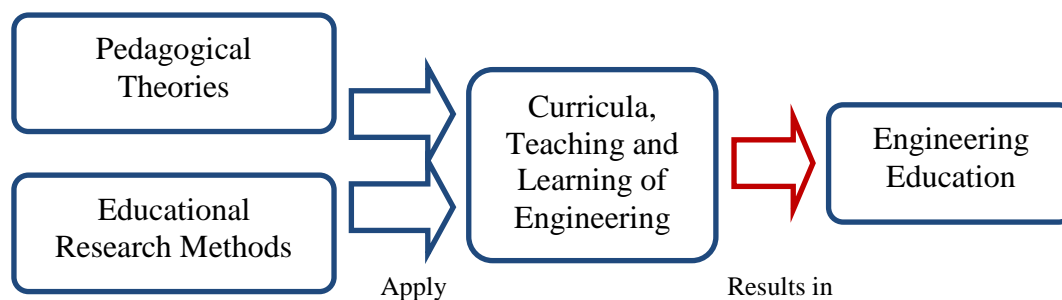


Figure 1.1. Conceptual diagram of engineering education research. Pedagogical theories and educational research methods are applied to engineering curricula, teaching and learning to result in a rigorous engineering education research outcome.

scholarly research in teaching and learning (Wankat et al., 2002; Rossiter et al., 2007; Borrego, 2007). The availability in funding, the change in the reward system for the career progress of engineering academics and the establishment of collaborative work with experts from pedagogy, psychology and social science play an essential role in advancing the scholarship of engineering education (Wankat et al., 2002; Olds et al., 2005; Streveler and Smith, 2006). For instance, the availability of funding in the UK for the establishment of the Engineering Subject Centre (engSC, 2000) and the Engineering Centre for Excellence in Teaching and Learning (engCETL, 2005) gave a significant push in the field nationwide and locally at Loughborough University. One of the main stated aims of the engSC is to support UK academics undertaking research in engineering education. The engCETL has been involved in supporting engineering education research at Loughborough University by awarding research funding to a number of research posts and PhD positions in engineering education. Funded engineering education research at engCETL includes projects investigating issues such as: peer assessment (Willmot and Crawford, 2007), distance learning (Blanchard et al., 2006) and industrial placement (Ahmed and Brown, 2009). The UK had an initial leadership in Europe with regard to engineering education research. There are many specialised British academic journals in engineering education such as the *Engineering Education* (EE) journal, the *International Journal of Electrical Engineering Education* (IJEEE) and the *International Journal of Mechanical Engineering Education* (IJMEE). The last two predate the initial publication of the *European Journal of Engineering Education* (EJEE), the only continental journal in the field.

In the US, the American Society for Engineering Education (ASEE) was established in 1893 as a non-profit organisation for advancing engineering education (ASEE, 2010). The ASEE publishes a recognised journal in the field, the *Journal of Engineering Education* (JEE). Some of the top US universities (e.g.

Purdue University, Virginia Tech. and Utah State University) have recently devoted independent departments to engineering education, which is very similar in structure and objectives to other engineering departments (e.g. electrical, mechanical and chemical). These universities started to run structured MSc/PhD programmes in *Engineering Education* (Borrego, 2006). Independent departments dedicated to engineering education are scarce in the US and do not exist elsewhere internationally. This reflects the early emerging status of engineering education as an independent field at the moment. Australia leads the area in Asia and the South Pacific. The Australian Association of Engineering Education was established in 1989 and publishes a specialised journal, the *Australasian Journal of Engineering Education* (AAEE). There is a dedicated centre for engineering education at Melbourne University. Some of the most recognised conferences in the engineering education area are the ASEE annual conference (USA), the FIE annual conference (USA), the engineering education biannual conference (UK), the ICEE annual conference (International) and the AAEE annual conference (Australia).

In brief, engineering education research holds a strategic value, as it would provide scientific evidence of effective teaching and learning methods in engineering that are capable of producing high quality, motivated and highly engaged graduates. At the current early emerging status of engineering education research, institutions that dedicate resources to conduct such research will have leadership in the future. The UK universities have a long history of emphasis on educational research compared with other EU countries. Many of the UK universities have an international reputation in engineering. Hence, the UK is in a particularly good position for further international leadership in the field of engineering education, e.g. by establishing structured MSc/PhD programmes in engineering education and/or making extra funding resources available to engineering staff who have an interest in conducting engineering education research. A newly opened MSc/PhD programme in the UK associated with good marketing policies would attract a significant number of international students, particularly in the absence of such programmes outside the US.

1.2 The Aim and Scope of the Thesis

The overall aim of the thesis is to enhance experimental education. The specific scope, as shown in Figure 1.2 is focused on a case applied to the Loughborough Process Control Lab, which is part of the control systems courses of the Chemical Engineering Department of Loughborough University. Control engineering is a

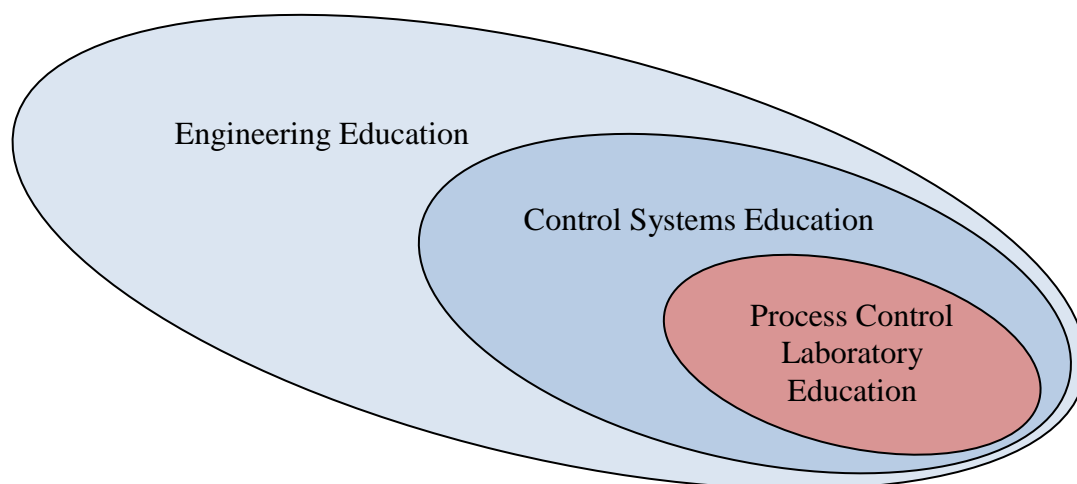


Figure 1.2. The thesis contributes to the engineering education literature and its specific scope is to enhance process control laboratory education which is a essential part of control systems education.

highly mathematical and multidisciplinary subject and generally perceived as difficult by students. Murray et al. (2003) consider the continuous use of experiments and the development of new laboratories and software tools to be an important element of control education and outreach. Practical experience is recommended to enhance undergraduate control engineering education (Antaklis et al., 1999). Associating control engineering subjects with supporting laboratory coursework generally aims to aid conceptual understanding and to show the applicability of theory in practice. The process control lab at Loughborough University is designed to achieve this purpose. However, laboratory education in general is reportedly inefficient; hence it is aimed to research better ways of teaching and learning of the process control lab. The next section introduces the research gap in the field. The Objectives of the Thesis

The main objectives of the thesis are: I) to develop a framework for the implementation of hybrid labs (combined hands-on, virtual and remote labs) for academics and web dissemination (the TriLab, see Chapter 5), with a case applied to the process control laboratory at the Chemical Engineering Department of Loughborough University; II) to investigate the impact of the integration of the components of the TriLab approach on students' learning in the light of modern pedagogical theories and by using educational research methods; and III) the proposal of a pedagogically informed model that may cope with the shortcomings of the classical approach of teaching and learning of

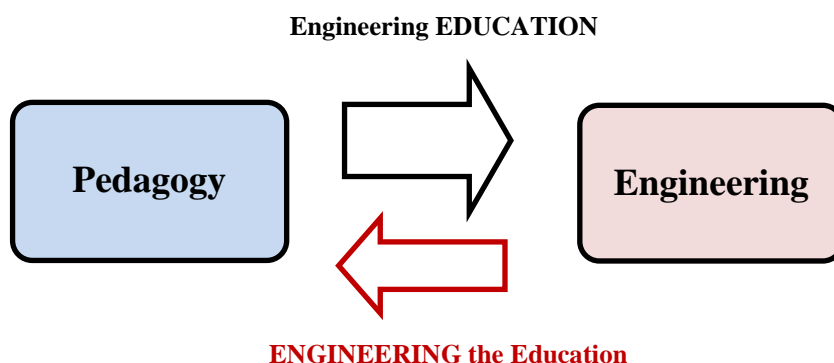


Figure 1.3. Conceptual model of the interaction between pedagogy and engineering in this thesis.

engineering labs. These aims are elaborated in Chapter 4, Chapter 5, Chapter 6 and Chapter 7. An overview of the mainstream pedagogical theories is given in Chapter 2 and a literature review of laboratories is provided in Chapter 3.

An emergent objective of this thesis, alongside the previous ones was IV) to use feedback theory of control systems engineering for modelling learning and pedagogical processes, as discussed in Chapter 8. The developed theory in Chapter 8 provides mathematical and engineering evidence of the importance of closing the loop during the learning process, e.g. providing effective feedback and formative assessment or activating self-regulated learning. Hence, rather than a passive relationship, where engineering is impacted by pedagogy (engineering EDUCATION), an active interaction has emerged during this project, where engineering is applied to pedagogy (ENGINEERING the education), as shown schematically in Figure 1.3.

1.3 Objectives of the Thesis in the Context of Gaps in the Field

The major relevant research gap in the laboratory education field is detailed in the literature review in Chapter 3. Briefly, it has been stated that laboratories are an essential element of engineering curricula (Corter et al., 2004; Feisel and Rosa, 2005) and have been reported as a rich arena of research (Ma and Nickerson, 2006; Hofstein and Lunetta, 2004). In particular, the integration of simulated and remote labs together with hands-on labs in the teaching and learning process has been recommended (Hofstein and Lunetta, 2004; Ma and Nickerson, 2006). Hands-on laboratories have many constraints. They are reported to be a poor platform for knowledge construction (Roth, 1994). Virtual labs (Blanchard et al., 2006) and remote labs (Nagy and Agachi, 2004) are new-

comers compared to the history of the hands-on lab and its role in engineering education. Combining two or three modes would result in a hybrid laboratory structure. The impact of such combination on the experiential learning of the students has not as yet been thoroughly investigated (Ma and Nickerson, 2006; Abdulwahed et al., 2008a). The literature, as shown in Chapter 3, seldom reports empirical investigations into utilizing the hybrid laboratory approach (Ma and Nickerson, 2006). Objectives (I) and (II) aim to address these gaps. Furthermore, there seems to be an absolute absence of pedagogical models for using hands-on laboratories in association with virtual or remote access (Abdulwahed and Nagy, 2009a). The scope of objective (III) is to address this gap. The scarcity of linking innovative practices by engineering educators with pedagogical theories has been noted by Wankat et al. (2002). The aim of enhancing the education of the process control laboratory implies developing and investigating the use of hybrid structures in the light of educational theories as elaborated in objectives (I, II, and III) which would contribute to the mentioned gap in the field; this is detailed in Chapters 5, 6 and 7. Alongside the project, it has been observed that many areas of educational research, such as feedback and formative assessment research (Juwah et al., 2004; Hattie and Timperley, 2007), self-regulated learning (Pintrich, 2000; Zimmerman, 2008), and instructional design (Dick et al., 2001; Gagne et al., 2005), correlate with concepts of control systems engineering, as elaborated in the review in Chapter 2. It has also been noted that methods of control systems engineering have seldom been used for quantitative modelling in pedagogy. Objective (IV) addresses this gap.

1.4 How the Research has been Tackled, a Brief Overview of the Used Methodologies in the Project

The methodology of tackling this project can be divided into two categories: 1) technical implementation methodology and 2) pedagogical investigation methodology. The technical methodology is concerned with the development of the hybrid TriLab approach and effective web dissemination of the remote component of the TriLab. LabVIEW (Travis and King, 2007) has been used for the TriLab development, while the Joomla web content management system (LeBlanc, 2007) has been used for web dissemination. On the other hand, the pedagogical investigation methodology is concerned with the development of proper educational experimental designs and the development of measurement instruments, data collection, analysis and evaluation. Experimental designs follow conventional educational research designs, as detailed by Cohen et al.

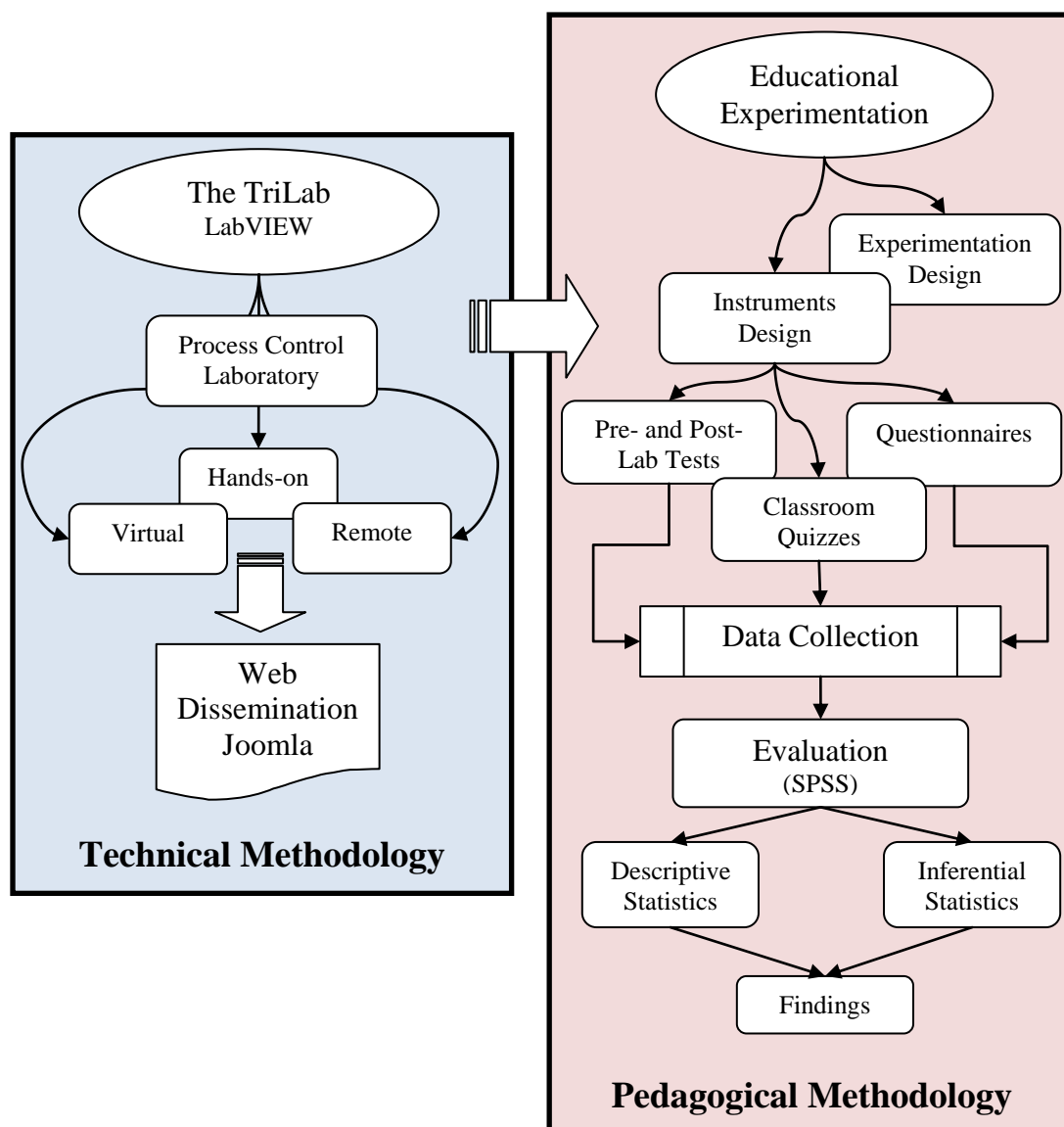


Figure 1.4. Conceptual model of the technical and pedagogical methodologies used throughout the thesis.

(2005). The measurement instruments include specially designed pre- and post-lab tests, questionnaires and multiple choice quizzes. The data was collected, mainly by delivering hard copy sheets to students (pre- and post-lab tests and questionnaires). The TurningPoint (2009) audience response system was used to collect data of the students' responses to in-class multiple-choice quizzes. The data has been analysed using the quantitative methods of the social sciences, in particular descriptive and inferential statistics, in association with the Software Package for Social Sciences (SPSS). Figure 1.4 shows a conceptual diagram of the methodology used. Further details are presented where appropriate in the relevant chapters. The next section provides an overview of the thesis chapters and its structure.

1.5 Overview of the Thesis Chapters and Structure

The thesis has been structured into nine chapters. The first three chapters set the scene of the work. Chapter 1 provides a general overview of the project; Chapter 2 and 3 present the literature review of pedagogical theories and laboratories. Chapter 4 introduces the Loughborough Process Control Lab, which is the main case study of the project. The methodologies, data analysis and development of models are discussed in Chapters 5, 6, 7 and 8. The thesis finally concludes with Chapter 9, which summarises the findings and provides future recommendations. The content of individual chapters is given briefly as follows:

Chapter 1- Introduction of the Thesis: A general overview of the thesis is provided in this chapter.

Chapter 2- Review on Pedagogy: This chapter introduces briefly the mainstream pedagogical theories, such as behaviourism, cognitivism and constructivism. The latter is the most modern educational school and many recent studies have shown its positive impact on engineering education. Experiential learning is one of the frequently reported constructivist approaches to teaching and learning in engineering education literature. This chapter expands particularly on Kolb's experiential learning theory, which is adopted as the pedagogical background for explaining the learning outcomes of laboratories and for the proposal of a new pedagogical model later in this thesis. Learning styles are an emergent pedagogical topic, and are concerned with the preferences of an individual to learning. A section is provided to introduce different models of learning styles. This is followed by a section showing that specific areas of pedagogical research correlate with engineering concepts, in particular feedback control systems. Towards the end of the chapter, a general discussion of the reviewed educational theories and final conclusions are provided.

Chapter 3- Literature Review of Laboratories: This chapter presents the literature review of laboratory education. It starts with an introductory section about the role of laboratories in engineering and science, followed by an explanation of their objectives and styles. In the subsequent sections, a review of the main modes of conducting laboratories, such as hands-on, virtual (simulated) and remote are presented. The advantages and the disadvantages of each mode are analysed in conjunction with the existing literature. An overview of the technologies used to implement virtual, hands-on and remote labs is provided with extended details of LabVIEW. This is followed by an overview of available technologies for web portals development. The chapter ends by showing that the

laboratory literature needs more empirical studies and concludes that hybrid labs have a high potential of being the most efficient way of conducting laboratory education.

Chapter 4- The Loughborough Process Control Lab: This chapter introduces the Loughborough Process Control Laboratory. The lab has served as a test bed for the technical development and pedagogical investigations of the subsequent chapters of this thesis. The lab consists of six pilot scale rigs and one modular rig. The components of the rig are described and the main concepts of the lab, such as instrumentation, PID (Proportional Integral Derivative) control and tuning, are introduced. The lab was initially designed to be a compulsory part of second year courses in the Chemical Engineering Department at Loughborough University, but it has been utilised in other courses, too. A detailed description of the experimental procedures of the laboratory sessions for the undergraduate courses is presented and is followed by concluding remarks.

Chapter 5- The TriLab Model of the Process Control Lab: This chapter introduces a new laboratory model, namely the TriLab. The model implements a triple access mode, where the hands-on experiment can be accessed remotely through the Internet and can also be conducted via a virtual (simulated) version within a uniform software environment. The TriLab approach is applied to the Loughborough Process Control Laboratory introduced in Chapter 4. The general architecture of implementing the TriLab with LabVIEW is provided. A development case of the TriLab with LabVIEW for the Armfield modular rig is detailed. Finally, the use of the Joomla web content management system for the Loughborough online lab portal development is presented, with an introduction to the tool used for the collection of web-site statistics. Finally, the TriLab as an enabler of the reusability of the experimental rigs is presented. This chapter introduces interested academics to a compact, one package recipe for constructing the TriLab with LabVIEW and for the World Wide Web outreach using Joomla.

Chapter 6- Towards a Pedagogically Enhanced Model of Laboratory Education: This chapter describes a model for laboratory education based on Kolb's experiential learning theory. The method was implemented using components of the TriLab model and has been applied to the teaching of the undergraduate process control laboratory in the Chemical Engineering Department at Loughborough University, United Kingdom. The argument that poor learning in the laboratory is due to insufficient activation of the prehension dimension of Kolb's cycle is posed. The experimental design and the data

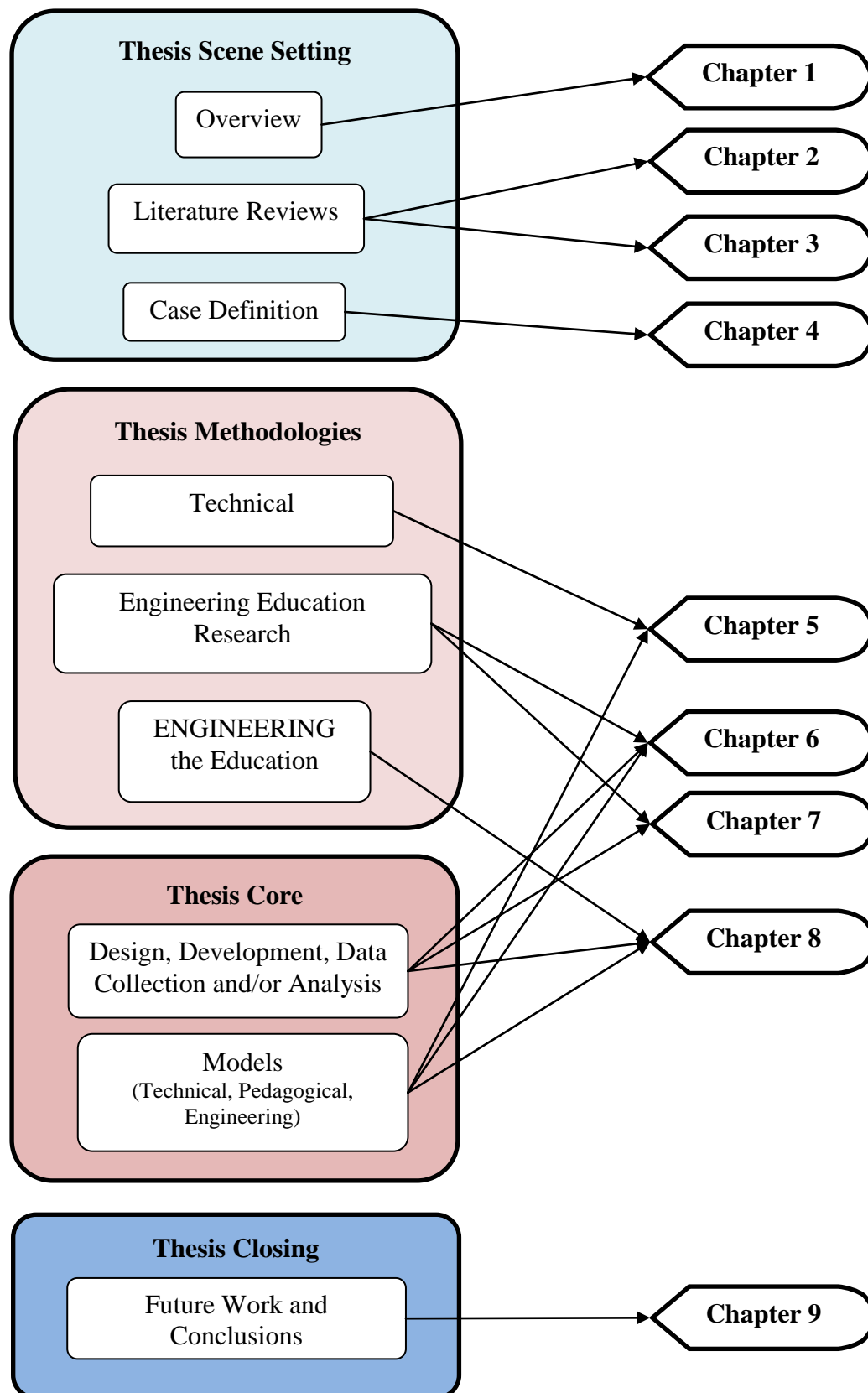


Figure 1.5. The general structure of the thesis and the main objectives of the chapters.

analysis of the laboratory learning outcomes have verified the proposed hypothesis, providing a pedagogical explanation. The quantitative analysis shows significant enhancement of the learning outcomes of the experimental group compared to the control group. The learning outcomes measured by means of pre- and post-lab tests were consistent over two academic years. Apart from the hands-on session, the proposed model involves additional activities, such as pre- and post-lab tests and virtual laboratory sessions. These activities are associated with Kolb's cycle to facilitate constructivist learning. The survey of the students' opinion of the process control lab has shown a positive attitude. This chapter represents the first laboratory education model that builds thoroughly on Kolb's experiential learning theory together with empirical analysis.

Chapter 7- Closing the Distance; Laboratory Experiments in the Classroom:

This chapter introduces a new classroom practice, whereby theory lectures are supplemented with remote experimentation in the class. The remote component of the TriLab has enabled the application of this approach in undergraduate and postgraduate courses in the Chemical Engineering Department of Loughborough University. This has been accompanied by measurements of the impact on students' attitude and learning. After the introductory sections, the research questions and the methodologies are outlined. Then individual sections further detail the data analysis and findings. Overall, the approach has left a positive impact on several aspects of learning and the students are comfortable with the method. The findings are summarised and linked with pedagogical theories. The chapter ends with concluding remarks.

Chapter 8- Pedagogy; a Control Systems Engineering Viewpoint: In this chapter, a control systems engineering view of pedagogy is presented. Quantitative dynamical models of learning are developed, namely open and closed-loop learning. The modelling process was inspired by the tank level experiment, which is introduced in Chapter 4. A new model of forgetting based on an engineering concept is introduced. The models are analysed and their implications are described. The models are then used as the basis for describing two modes of lecturing: open- and closed-loop. A technology based on the audience response system for closing the loop in the lectures is introduced with empirical findings of the students' attitude towards it. Empirical findings in the educational literature that support the predictions of the closed-loop models are provided. The discussion about considering the constructivist laboratory model that is introduced in Chapter 6 as a closed-loop learning enabler is explained in

detail. Finally, a section proposes the ‘Systems Pedagogy’ concept as a field for engineering the education is provided and is followed by concluding remarks.

Chapter 9- Future Work and Conclusions: This chapter provides a summary of the project findings and future work.

The emphasis and main objectives of the individual chapters of the thesis is shown in Figure 1.5.

1.6 The PhD Project Outcomes

The main outcomes of the project are:

- **The TriLab model:** A technical model of developing a hybrid laboratory (virtual, hands-on and remote) in addition to web dissemination, with a case study applied to a process control lab.
- **The iLough-Lab:** The first remote laboratory portal of Loughborough University and one of the few available in the UK.
- **Abdulwahed-Nagy Constructivist Laboratory Model:** A constructivist pedagogical model of laboratory education that integrates components of the TriLab and based thoroughly on Kolb’s experiential learning theory.
- **Systems Pedagogy, Concept and Models:** Control systems models of pedagogical processes have been developed, and a proposal of the ‘Systems Pedagogy’ concept has been suggested.
- **Dissemination:** 1) Two published journal articles: The Abdulwahed-Nagy model (Abdulwahed and Nagy, 2009a) has been published in the *Journal of Engineering Education* (JEE), a high-impact factor educational journal (IF=3 for 2007); a systemic model of project based learning (Abdulwahed et al., 2009) has been published in the *Journal of Education, Information, and Cybernetics*. The article was selected for publication as one of the top EISTA 2008 conference papers. The author has been invited to join the journal editorial advisory board. 2) A workshop on laboratories with colleagues from the UK and Australia. 3) Many refereed conference contributions: the project progress has been demonstrated at a number of international conferences. Publications list can be found towards the thesis end.

The project has been highly interdisciplinary and included elements of LabVIEW programming, online portal development, educational experimentation design, development of instruments for educational measurements (questionnaires,

tests, quizzes), the use of descriptive and inferential statistics for data analysis with SPSS (Statistical Package for the Social Sciences), literature reviews and the development of control systems models of educational processes.

1.7 Difficulties and Constraints

The project is in the field of engineering education, which implies crossing the boundaries of a robust quantitative and hard science (engineering) to generally qualitative soft science (pedagogy). This may require leaving the comfort zone the engineer (Wankat et al., 2002), the miss-match between the learning styles of engineering and pedagogy has been noted by Kolb (1984). Defining variables to measure and developing reliable instruments is much easier in science and engineering than in pedagogy (Wankat et al., 2002). It is barely possible to conduct pedagogical research without confounding factors. Engineers are much more accustomed to work with precisely defined variables (Wankat et al., 2002). Pedagogy holds different vocabularies, priorities and conceptions of research. Research in engineering education requires adopting different methods to those used in engineering (Streveler and Smith, 2006). The other main constraint is represented by the fact that conducting a comparative empirical investigation in engineering education is impeded by many factors. One of these factors is the relatively fewer number of registered students in engineering classes, e.g. MSc classes. There are also complications and ethical issues in relation to forming two groups of students with different teaching approaches (Wankat et al., 2002). Ethical and logistical constraints are further discussed in Chapter 6.

1.8 Conclusions

This chapter provided an overall overview of the thesis. After introducing the field of engineering education research, the thesis scope was defined. A brief overview of the research gap is shown and is followed by a description of the main aims of the thesis. A section describing how the research was tackled, with an overview of the methodologies used has been provided. In particular the methodologies were categorised in two types, technical and pedagogical. A general overview of the content of the thesis chapters and their structure has been shown. There are two chapters for the review of the literature, and four chapters in which the methodologies are developed, data analysed and models proposed. Then a section has been provided to show the main outcomes of the research project. The final section before conclusions introduced the main difficulties and constraints of this research project.

Chapter 2.

REVIEW OF PEDAGOGY

Overview

This chapter introduces briefly the mainstream pedagogical theories, such as behaviourism, cognitivism, and constructivism. The latter is the most modern educational school and many recent studies have shown its positive impact on engineering education. Experiential learning is one of the frequently reported constructivist approaches to teaching and learning in engineering education literature. This chapter expands particularly on Kolb's experiential learning theory, which is adopted as the pedagogical background for explaining the learning outcomes of laboratories and for the proposal of the new pedagogical model later in this thesis. Learning styles are an emergent pedagogical topic, and are concerned with the preferences of an individual to learning. A section is provided to introduce different models of learning styles. This is followed by a section showing that specific areas of pedagogical research correlate with engineering concepts, in particular feedback control systems. Towards the end of the chapter, a general discussion of the reviewed educational theories and final conclusions are provided.

2.1 Behaviourism

Early educational systems were designed based on behaviourist approaches to learning. The theory emerged as a result of the work of Thorndike (1913), Pavlov (1927) and Skinner (1953). The central focus of behaviourism is on the individual's behaviour during learning in response to stimuli (Skinner, 1974). Some of the main principles of behaviourism that constitute learning are consequences, reinforcers, punishers, immediacy of consequences, shaping, extinction, schedule of reinforcement and maintenance (Bigge and Shermis, 1999; Malott et al., 1999; Kazdin, 2000). The consequences principle implies that positive consequences strengthen behaviour, while negative consequences weaken it. Hence, a stimulus with positive consequences can enhance learning (shaped by the increased frequency of behaviour). The principle of reinforcers implies applying consequences that increase the frequency of behaviour; for

instance, rewards for learning achievement can be considered as reinforcers. Punishers, on the other hand, are consequences that weaken behaviour. The immediacy of consequences principle implies that delayed consequences have less effect on behaviour than immediate consequences. Hence, an immediate small reinforcing action has a higher impact than a larger but delayed one (Kulik and Kulik, 1988). The shaping principle implies applying consequences or punishers that shape behaviour in a desired way. The extinction principle implies that behaviour is weakened when reinforcers are withdrawn, e.g. if an award for success is withdrawn, the motivation to achieving a greater degree of effort decreases. The principle of the schedule of reinforcement includes the number of reinforcements given, the time interval in between them and the nature of the potential behaviour to emerge. The maintenance principle refers to those behaviours that persist after a reinforcement withdrawal.

Hence, behaviourism perceives learning as a passive process shaped by the stimuli of the environment. Behaviourism emphasises that learning can take place by observation of others' behaviour (Schunk, 2000). Cognitivism developed later, as a response to the passive approach of behaviourism. Cognitivism tries to understand the internal processes underlying learning and information acquisition. Cognitivism is introduced in the next section.

2.2 Cognitivism

Cognitivism (Kulhavy and Wager, 1993; Atkinson and Shiffrin, 1968; Squire et al., 1993; Martin, 1993; Baddeley, 1999) perceives learning as an internal process, which takes place in the mind and involves memory, reflection, motivation and metacognition. Cognitivism arises from cognitive psychology, which studies the mental mechanisms of learning, problem solving, information reception and processing, memory, intelligence, language and human mental development. This section presents elements of cognitivism such as the information processing model, the dual coding theory and the forgetting factor, which are used later on in the thesis to explain the empirical findings or for modelling.

2.2.1 The Forgetting Factor

The impact of the forgetting factor on information retention has been comprehensively studied. The forgetting factor was originally proposed by the German psychologist Herman Ebbinghaus (1913). Ebbinghaus found that humans forget information exponentially. Many models, mainly exponential or power based, were proposed later, and examples of these models can be found in

the work of Loftus (1985), Wixted and Obese (1991), White (1985), Rubin (1982), Rubin et al. (1999), Mensink and Raaijmakers (1988) and Wickelgren (1972 & 1974). All of these models share the common features that the forgetting rate is higher for information learnt recently and that the rate declines with time. An empirical comparison of different forgetting factors can be found in the work of Nembhard and Osothsilp (2001). The forgetting rate can increase for many reasons, such as when learning complicated tasks (Nembhard, 2000), when the learner has negative mood (Bäuml and Kuhbandner, 2009), lack of testing and assessment (Wheeler et al., 2003), lack of sleep (Born et al., 2006) and drinking alcohol prior to learning (Lister et al., 1987). Ebbinghaus's basic model of forgetting will be used in Chapter 8 in the modelling process of open loop learning. Also, a new model of forgetting inspired by an engineering approach will be developed in Chapter 8.

2.2.2 The Information Processing Theory (IPT)

The information processing theory (Atkinson and Shiffrin, 1968) of learning and memory functionality has been widely accepted during the last few decades (Slavin, 2005). The theory explains the process of information absorption and storage in the human mind. This information is permanently received in the so-called *sensory register* in the mind through the senses. Most of this information is discarded immediately if not attended. Some is accommodated for a short period in the so-called *working memory* or *short-term memory* and then forgotten, while some is stored in the so-called *long-term memory* for much longer. The theory originates from the early works of Atkinson and Shiffrin (1968) on human memory.

Figure 2.1 shows the information processing mechanism of the human memory. The information first reaches a person's senses as external stimulation and is passed to a sensory register where some is discarded immediately and some is passed to the working memory space. There, some information will be forgotten and some will be processed again for storage in the long-term memory. The components of the IPT model of memory are:

Sensory register: The sensory register receives a large amount of information from different senses, such as sight, hearing, smell and taste. This information is held for approximately half a second for visual stimuli and three seconds for auditory stimuli (Hollands and Wickens, 1999), then it disappears if it is not further processed. To foster processing, attention should be directed toward the received information. The implication of this functionality on the teaching and

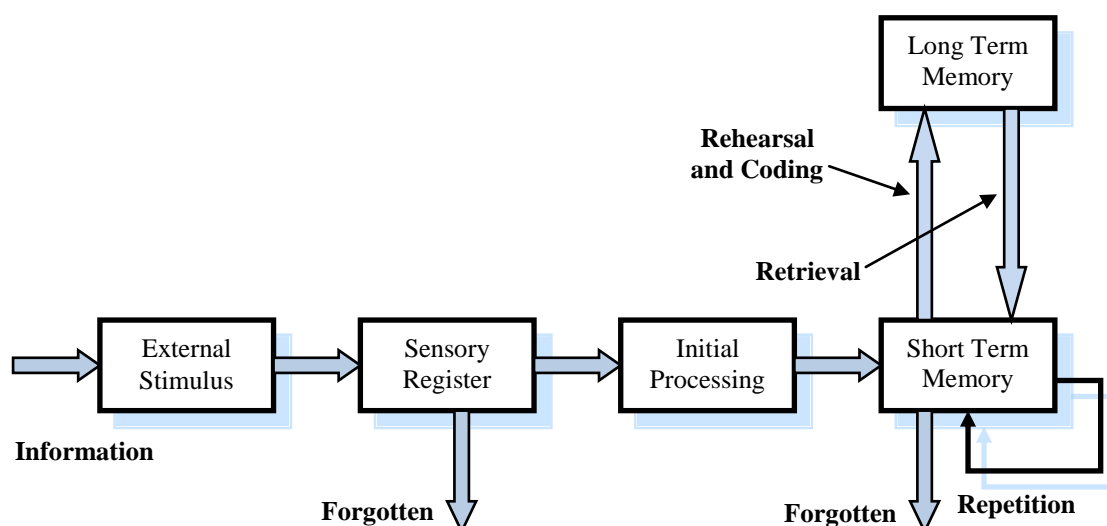


Figure 2.1. The information processing model of human memory. The model distinguishes between two different memories, the short term memory and the long term memory.

learning process is that students should be made aware of which information is the most important to retain.

Short-term or working memory: Once a person pays attention to the perceived information in the sensory register, it is transmitted to the working memory (Ericsson and Kintsch, 1995), which is also called short-term memory (Squire et al., 1993). The working memory is where the information currently being received is processed. It is the place where the mind organises the information for long-term storage or for forgetting, and connects it to other information.

The short-term memory has a limited capacity and information can only be held for up to 30 seconds. The normal capacity of the working memory is five to nine bits of information. In other words, a person can think about five to nine things at the same time. The short-term memory is the channel for transferring information from the sensory register to the long-term memory.

The limited capacity of the working memory means that it is a bottleneck in this process. The information has an enhanced chance to be transferred to the long-term memory when it is retained for a longer time in the working memory; however, the upper constraint of such retention is limited to 30 seconds. One good strategy to reload the working memory with the information is to think about it again and again. This process is called *rehearsal*. The working memory can recall information from the long-term memory to operate on.

The working memory in the information processing model is analogous to the Random Access Memory (RAM) in personal computers (PCs).

Long-term memory: Information is kept for a longer period in the long-term memory. Learning strategies are also stored in the long-term memory (Ericsson and Kintsch, 1995). There are three different memory types in the long-term memory: the episodic memory (Craik and Tulving, 1975; Martin, 1993), the semantic memory (Martin and Chao, 2001) and the procedural memory (Cohen and Bacdayan, 1994). The *episodic memory* is associated with the kinetic, auditory and visual events that a person has experienced. The episodic memory contains images of experiences organised by when and where they happened. The *semantic memory* is associated with conceptual attributes, facts and general information. It is organised as networks of connected ideas or relationships called *schemata* (Voss et al., 1995). The *procedural memory* is the place where the algorithms a person uses to perform tasks are stored. These procedures are stored as stimuli-response pairs.

The concept of episodic and semantic memory has led to the *dual coding theory* (Clark and Paivio, 1991), which suggests that information is stored both visually (linkage with episodic memory) and verbally (linkage with semantic memory). This information is retained more successfully than the information that is stored in only one way.

2.2.3 Implications of the IPT on Education

Understanding the mechanism by which the human memory works and the hypothesis that it is divided into different types can impact educational design in many ways, as described below.

Implication of short-term memory on education: To facilitate the retaining of information, a teacher should allocate time for rehearsal in the classroom. The implication of the limited capacity of short-term memory is that one cannot expose students to too many new ideas at once. This will lead to a cognitive overload (Sweller et al., 1998). If the new ideas are linked with the previous knowledge of the student, e.g. linked with information that is stored in the long-term memory, this will trigger reciprocal communication between the short- and long-term memories and will enforce autonomous retaining of the new ideas in the long-term memory, freeing up space for additional new ideas to be gathered by the short-term memory.

Implication of long-term memory on education: Incorporating visual or auditory images in instruction will enhance effective storage in the episodic

memory and further enhance learning (Martin, 1993). Using other active forms associated with episodic memory alongside the learning process such as projects, simulations and teamwork results in an enhanced learning experience. The implication of the schemata concept is that the new information can be retained better when it maps well with already developed schemata (Anderson, 1985). Bahrick (1991) found that retention drops quickly in the first few weeks of instruction, but the retained information is sustained for much longer. This implies that repeating information after a couple of weeks can be used as an instrument for fixing information in the long-term memory.

2.3 Constructivism

Constructivist pedagogy is a modern paradigm that has been significantly impacted by cognitivism (Hergenhahn and Olson, 2004); however, it holds a holistic approach to pedagogy and learning as opposed to the microscopic focus of cognitivism on the internal mechanisms that underline learning processes. Constructivism perceives learning as a process of constructing knowledge by individuals themselves as opposed to the passive teacher-student model (Kolb, 1984; Caine and Caine, 1991; Tynjälä, 1999; Richardson, 2003; Piaget, 1978; Brown et al., 1989; Steffe and Gale, 1995; Gergen, 1995; Mayer, 1999). Learning should focus on concepts and contextualisation instead of instructing isolated facts (Brooks and Brooks, 1993). In the process of knowledge creation, students link new knowledge with their previous knowledge. Constructivist pedagogy emphasises the student's social interaction with peers and the teacher (Palincsar, 1998). Consideration should be given to the student's preferred *learning style* (Kolb, 1984).

One important pioneer of educational constructivism is John Dewey (1938), an American philosopher, psychologist and educational reformer (Kolb, 1984). Dewey (1938) asserted the need for educational reform. Students should learn critical thinking rather than memorizing lessons. Piaget is considered as a great pioneer of the knowledge constructivism theory. Piaget (1978) introduced the term *Constructivist Epistemology* to express his theory of learning. Piaget viewed learning as a continuous process of destabilizing mental equilibrium when new facts are encountered, and the equilibrium is then retained by either assimilation or accommodation. This in turn upgrades the level of thinking due to the reforming of the internal mental model (Piaget, 1978). The Russian sociologist Vygotsky (1978) asserts also that constructing knowledge occurs after disequilibrium. Constructivist pedagogy argues that reality cannot be

constructed in the mind without experiencing it (Kolb, 1984). Since constructivism emphasises the individual's important role in knowledge construction, the constructivist strategies in teaching are often called *student-centred instruction*. The constructivist pedagogy as theory has its roots many decades back, however empirical research into constructivist pedagogy started only in the early 1990s (Richardson, 2003).

Some of the main pillars of constructivist pedagogy are: learning should be associated with the authentic real-world environment; social interaction is an important part of learning; the taught elements should be made relevant to the learner; the taught elements should be linked with the learner's previous knowledge; it is important to facilitate continuous formative assessment mechanisms; students' autonomy should be fostered through encouraging self-regulated learning, self-esteem and motivation; teachers should act as orchestra synchronisers rather than speech givers; and teachers should consider multiple representations of their teachings (Richardson, 2003; Doolittle, 1999).

Authentic teaching by exposing students to real world problems in the classroom is essential. For instance, exploiting real experiments in theoretical lectures, such as shown in Chapter 7, and providing the students with time to reflect is a constructivist approach. Constructivist learning forms are very diverse. Internships, field placements, assignments, role playing, games, cooperative problem solving, project-based learning, service learning, laboratory studies, experiential learning, field projects and many others are classified as constructivist learning practices. Richardson (2003) calls for more empirical research on constructivist methodologies that engage students in the learning process. Such empirical research will help to formulate a theory that provides an understanding and description of effective constructivist practices. It is hoped that the findings of this thesis, e.g. Chapter 6 and Chapter 7, will contribute to the body of knowledge of constructivist engineering pedagogy. The next subsection introduces the constructivist experiential learning approach.

2.3.1 Experiential Learning

Experiential Learning (EL) is a constructivist pedagogy approach. Experiential learning is an ancient practice that embraces the philosophy of 'Learning by Doing'. One can argue that the experiential approach is probably the oldest form of learning and is the originator of advanced science, given that early human innovations were the outcome of experiences rather than theories. However, experiential learning was not recognised as a structured pedagogical

methodology until the 20th century (Kolb, 1984). Dewey (1938) emphasises the role of real experience in education during the 1920s and 30s. Later on, during the 1960s and 1970s, experiential learning theory flourished as a result of the contributions of many psychologists, sociologists and educators. Among these are Piaget, Hahn, Chickering, Tumin, Bloom, Friere, Gardner and Lewin (Kolb, 1984). Experiential learning, in its simplest definition, can be thought of as the process of evolving knowledge through experience. EL is a general term that may involve a wide spectrum of activities. Many experiential learning models in which the learning process is divided into distinct stages have been proposed in the last four decades (Bacon, 1987; Kolb, 1984; Priest and Grass, 1997). A brief overview of EL models is provided in the next subsection.

2.3.2 Experiential Learning Models

A two-stage model of EL emphasises the interaction ‘Experience; Reflection’ (Bacon, 1987). Greenaway’s (1995) three-stage model ‘Experience; Reflection; Planning’ suggests that planning a future experience would be helpful to increase the learning outcome. Kolb in his 6000+ times cited book on experiential learning (Kolb, 1984) has built on Dewey’s theory of education (Dewey, 1938) and Lewin’s social psychology (Lewin, 1942) and developed a four-stage EL model with the elements: concrete experience, reflective observation, abstract conceptualisation and active experimentation. Pfeiffer and Jons (1975) propose a five-stage EL model: Experiencing, Publishing, Processing, Generalizing and Applying. Joplin (1981) suggests a five-stage EL model comprising the following phases: Focus, Action, Support, Feedback and Debriefing. The EL model of Priest and Grass (1997) consists of six stages: Experience, Induce, Generalise, Deduce, Apply and Evaluate.

2.3.3 Kolb’s Experiential Learning Model

Kolb’s Experiential Learning Theory (ELT) is the best received in the field (Tennant, 1997). The constructivist pedagogy is viewed as a pedagogical framework or a school of thought rather than a well-structured theory (Richardson, 2003). On the other hand, Kolb’s experiential learning theory provides more clear mechanisms of constructivist teaching and learning design. ELT emphasises the role of experience in learning and the importance of developing linkage between classroom practices and the real world (Kolb, 1984), which is in correlation with the emphasis of constructivist pedagogy on authentic learning (Doolittle, 1999).

Kolb (1984) defines learning as “*the process whereby knowledge is created through transformation of experience*”. In his work, Kolb built upon the works of Dewey (1938), Lewin (1942) and Piaget (1978), and suggested that effective learning should pass a cycle of four phases:

- Concrete Experience (CE)
- Reflective Observation (RO)
- Abstract Conceptualisation (AC)
- Active Experimentation (AE)

According to the ELT of Kolb, optimal learning takes place when the learners have an adequate balance of the previous four stages. These are the stages by which the process of creating knowledge through transformation of experience takes place. Learning, according to Kolb, requires that individuals should first detect, depict or grasp knowledge, and then a phase of construction should take place to complete the learning process. The combination of the four stages is called Kolb’s experiential learning cycle and is shown in Figure 2.2.

The vertical axis represents the knowledge-grasping dimension, or the *prehension dimension*, by which knowledge can be grasped through *apprehension* (the concrete experience extreme) or by *comprehension* (the abstract conceptualisation extreme), or by a mix of both. The horizontal axis represents the *knowledge transformation* or *knowledge construction* dimension. Construction can be done via *intention* (the reflective observation extreme) or via *extension* (active experimentation). Kolb’s hypothesis of the two dimensional nature of knowledge building was drawn from the convergent evidence from philosophy, psychology and physiology (Kolb, 1984). Previous to this hypothesis, the literature did not distinguish between grasping and transformation, combining them in one axis. Kolb distinguishes apprehension and comprehension as independent modes of grasping knowledge, and intention and extension as independent modes of transforming experience. Furthermore, he states that the four modes are equally important in contributing to the learning process. This proposal is in disagreement with Piaget’s concept, according to which comprehension and intension are superior processes (Piaget, 1978).

Looking at the current traditional teaching methods in higher education, one can see that Piaget’s model of comprehension-intention is the most common approach. Traditional teaching methods place more emphasis on theory taught in classical classroom settings and on reflection on this theory by written exams.

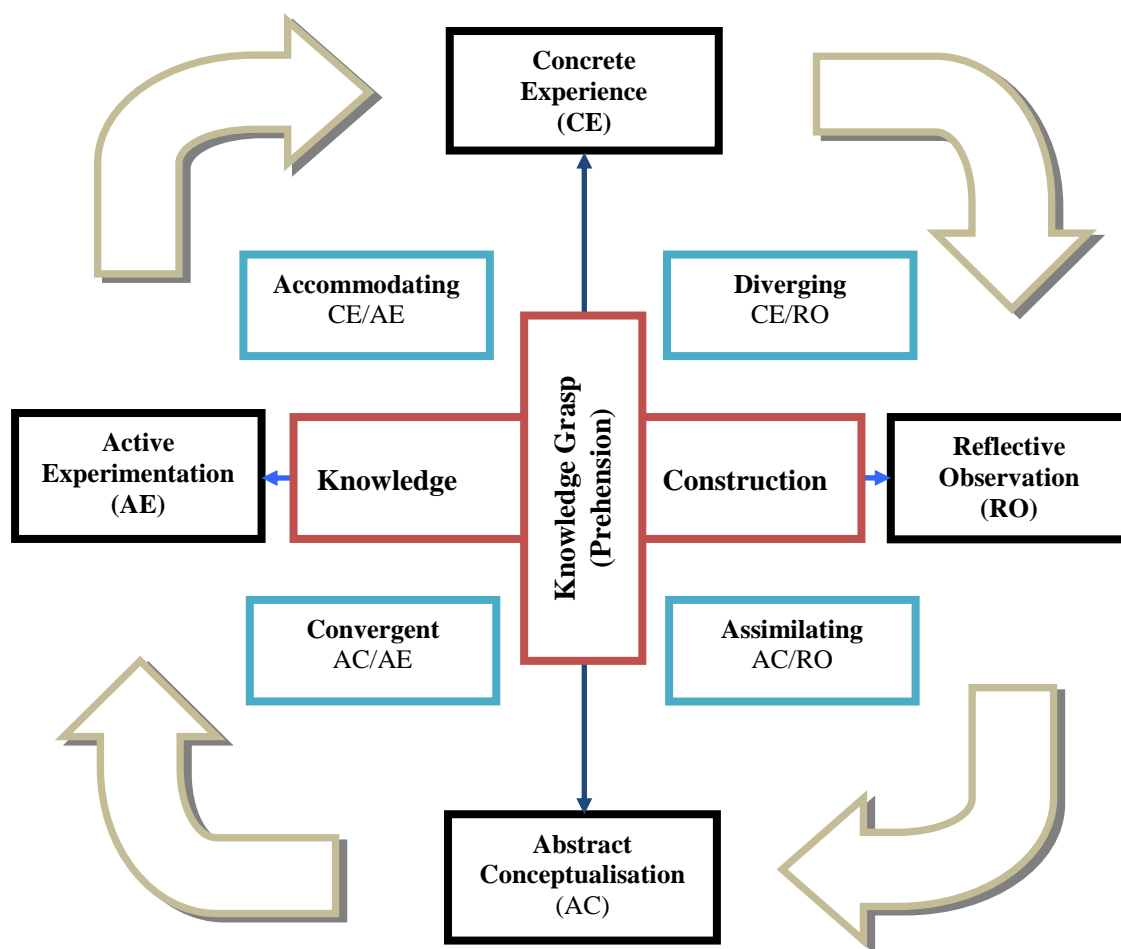


Figure 2.2. Kolb's experiential learning cycle. The black boxes represent the four phases of learning, CE, RO, AC, and AE. The red boxes represent the two dimensions of learning, the vertical one is the knowledge grasp and the horizontal one is the knowledge construction. The blue boxes represent learning styles of the individuals based on different combinations of learning preferences.

In contrast, Kolb's experiential learning theory has a strong implication on allowing balanced room for each mode, apprehension, comprehension, intention and extension, in the learning process.

Kolb's ELT provides a theoretical framework, which can be used to design better teaching and learning strategies that fit optimally with the human mental process of knowledge acquisition and construction. *A hybrid combination of the previous elementary modes in the learning process produces a higher level of learning.* Kolb's ELT is used as a pedagogical profile in explaining the poor learning outcomes of laboratory education and developing a novel laboratory education model in Chapter 6.

2.3.4 Kolb's ELT in Engineering Education

Engineering has a strong experiential element; however, in most cases it is built upon complex mathematical and physical principles, which need several iterations to comprehend and extend to the specific engineering domain. The cyclic nature of Kolb's EL model and its emphasis on the two modes of experience, the CE and the AE, makes it relevant for engineering education design (Felder et al., 2000; Bender, 2001). Wankat et al. (2002) indicate that Kolb's (1984) theory is often cited in the articles of the *Journal of Engineering Education*.

The use of Kolb's theories in engineering education research and design can be traced in many recent studies (Moor and Piergiovanni, 2003; Kamis and Topi, 2007; Bender, 2001; Lagoudas et al., 2000; Plett et al., 2006; David et al., 2002; Stice, 1987), resulting in positive findings in most cases. Based on Kolb's theory, Moor and Piergiovanni (2003) justify the advantages of blending classroom theory with experiments. Kamis and Topi (2007) found a Kolb-based approach to problem solving to be useful. Bender (2001) explains a major reform of taught courses in the Engineering Design department of the Technical University of Berlin using Kolb's theory and highlights the importance of incorporating the four dimensions of learning in the design of lectures.

Lagoudas et al. (2000) restructured five core undergraduate engineering courses using Kolb's cycle as a pedagogical background for this process. They relied on computer software and simulations in their implementation of Kolb's theory (Lagoudas et al., 2000). Plett et al. (2006) redesigned three engineering courses building upon Kolb's theories and the 4MAT system (McCarthy, 1986). The design was successful and led to receiving additional grant for curriculum design (Plett et al., 2006). David et al. (2002) used Kolb's experiential learning cycle as a pedagogical basis for designing learning experiences for students. One key finding in their study was that providing balanced learning experiences to students, based on the four stages of Kolb's cycle, led to deeper learning and longer retention of information.

Stice (1987) also implemented teaching strategies in class that can accommodate all four stages of Kolb's cycle to improve the learning process for undergraduate students. It is worth mentioning that literature regarding the use of Kolb's experiential learning theories for the design and evaluation of laboratory education is scarce (Abdulwahed and Nagy, 2009a).

2.4 Learning Styles

Individuals learn with their own preferences. Constructivist pedagogy acknowledges the differences between learners and emphasises taking them into consideration when designing teaching and learning activities. In the light of Kolb's experiential learning theory discussed earlier, there are two modes of grasping knowledge (apprehension and comprehension), and two modes of transferring the knowledge (intention and extension). Hence, individuals also tend to grasp knowledge with a varied balance between the two extremes of the prehension axis, and also tend to transform this knowledge with a varied balance between intention and extension. This results in four main combinations that individuals use for a successful learning process. The first is grasping information via Apprehension (CE) and transforming it into knowledge via Intention (RO), leading to a *Divergent Learning Style*. The second is grasping via Apprehension (CE) and transformation via Extension (AE), leading to an *Accommodative Learning Style*. The third is grasping via Comprehension (AC) and transformation via Intention (RO), leading to an *Assimilative Learning Style*. The fourth is grasping via Comprehension (AC) and transformation via Extension (AE), leading to a *Convergent Learning Style*. Kolb suggests a Learning Style (LS) model that is composed of the previous four main categories (Kolb, 1984) and developed an inventory for assessing individuals' learning styles (Kolb, 1999).

The fact that individual learners have their own learning styles has been asserted by many pedagogy and psychology researchers, leading to other LS models. The Index of Learning Styles (ILS) model was developed by Felder, Silverman and Solomon (Felder and Silverman, 1988; Solomon and Felder, 2004). This model recognises four main learning styles, which are: Active and Reflective; Sensing and Intuitive; Visual and Verbal; and Sequential and Global. Solomon and Felder developed a free online instrument for assessing the individual preference in learning. McCarthy (1986) developed the 4MAT LS model, which identifies four styles of learning: Innovative, Analytic, Common Sense and Dynamic. Inspired by cognitivism, Fleming and Mills (1992) proposed the VARK LS model, which recognises the following styles of learning: Visual (V), Aural (A), Read/Write (R/W) and Kinesthetic (K), depending on the learner's preference of information reception, e.g. visual learner (V style) or textual learner (R/W style).

The learning styles concept implies that teaching and learning design should be achieved in a way that accommodates, as much as possible, the differences in ways learners tend to construct knowledge.

Applying effective pedagogies on the teaching and learning of engineering courses would result in higher quality engineering education. However, there is one interesting question to ask: *is there any relationship between engineering theories and pedagogical theories?* The next section shows that there is a correlation between areas of pedagogical research and the control systems field of engineering.

2.5 Engineering Concepts of Feedback, Systems and Control in the Pedagogical Literature

Despite the scant use of quantitative methods of control systems engineering in pedagogy (Rompelman and Graaff, 2006; Abdulwahed et al., 2009), one can observe a common language in many descriptive pedagogical papers. Furthermore, there are traces of relative consensus. To illustrate this, a correlation from the educational literature with control systems is shown. A considerable body of pedagogical research has embraced many principles of control systems engineering design. Particular areas are educational feedback and formative assessment research (Hattie and Timperley, 2007; Shute, 2008), self-regulated learning research (Zimmerman, 1989; Butler and Winne, 1995) and instructional design (Gustafson and Branch, 1997; Dick et al., 2001). Fundamental pedagogical issues such as maximizing learning, eliminating differences, regulating learning and systematic design of learning can be viewed from the angle of control systems engineering (and its related disciplines). In the next subsections, a short introduction to the control systems feedback loop is provided, followed by a review of pedagogical research that correlates with control systems engineering.

2.5.1 Brief Introduction to the Control Systems Feedback Loop

In principle, control systems are mechanisms by which a measured behaviour of a system is used to modify it by actuation (Goodwin et al., 2001). Feedback is the core concept in control systems engineering, and it is used as an artificial tool for achieving regulation and uncertainty management in technical systems (Åström and Murray, 2008).

In this approach, the performance of the running system is measured and compared to a reference signal. The error is then calculated and used to actuate the system in a way that reduces the discrepancy, as shown in Figure 2.3. In the next subsections, it will be shown that some educational research literature shares similar concepts to the feedback control system.

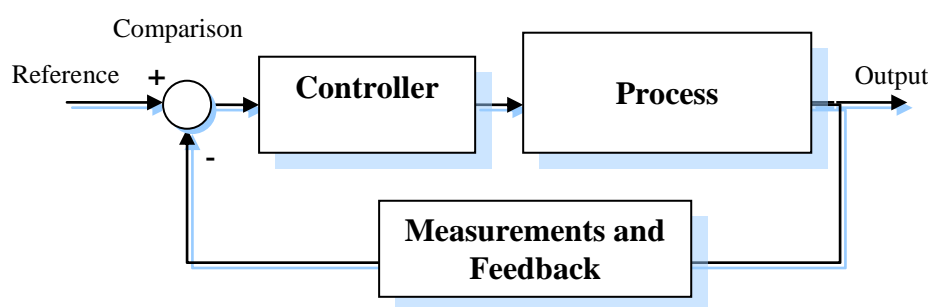


Figure 2.3. Feedback control system loop.

2.5.2 Feedback and Formative Assessment Research

Feedback in the pedagogical literature is defined as “information provided by an agent (e.g. teacher, peer, book, parent, experience) regarding aspects of one’s performance or understanding” (Hattie and Timperley, 2007). A similar definition is proposed by Johnson and Johnson (1993). Feedback has been considered as an essential element in mainstream pedagogical theories such as behaviourism (Skinner, 1953), cognitivism (Kulhavy and Wager, 1993) and constructivism (Kolb, 1984; Jonassen, 1999; Mayer, 1999; Willis, 2000). Feedback has been emphasised as an important factor for effective instruction (Collis et al., 2001; Dick et al., 2001; Race, 2005). Incorporating feedback into teaching and learning has been frequently reported to enhance the learning process in comparison with cases where no feedback has been provided (Hanna, 1976; Krause et al., 2009). Providing feedback can reduce the cognitive load, especially for novice learners (Sweller et al., 1998). It is argued that if any learning is achieved, a form of feedback should have been established (Stermann, 2006). Knowledge of results or knowledge of what is a correct answer are considered as feedback (Krause et al., 2009). However, a more effective form is the elaborated feedback, where information on how to improve the answer is provided (Pridemore and Klein, 1995; Moreno, 2004). It is argued that self-feedback elaboration is a distinguishing factor between very effective and less effective learners (Hattie and Timperley, 2007). Comprehensive guidelines for delivering formative feedback to enhance learning (things to do or avoid), for delivering formative feedback with respect to timing issues and guidelines for providing formative feedback in relation to the learners’ characteristics are outlined by Shute (2008).

The Hattie and Timperley (2007) model of effective feedback proposes that feedback must highlight three main questions: “Where am I going? (What are the

goals?)”, “How am I going? (What progress is being made toward the goal?)” and “Where to next? (What activities are needed to make better progress?)”. Feedback in Hattie and Timperley’s proposal is a mechanism for reducing the gap between the current and desired understanding of learning. Control systems engineering, in contrast, is a quantitative and conceptual way of representing such a descriptive mechanism. The three questions of Hattie and Timperley are very relevant to the feedback control loop shown in Figure 2.3. The first question is equivalent to the reference signal (setpoint); without a clear setpoint, the control system will lose its objectives. The importance of stating clear goals or objectives of learning (e.g. setpoint) to establish good feedback has been emphasised in many other pedagogical articles (Earley et al., 1990; Locke and Latham, 1990). The second question is equivalent to the measurement unit and the third question is equivalent to the controller that steers the process towards its aimed goals.

Formative assessment, a main category of feedback in educational research, is a process that involves assessing the learning outcomes of a learner, formally or informally, and feeding back him/her the assessed outcome. Formative assessment may involve activities such as classroom questioning, peer- and self-assessment and the formative use of summative tests (Black et al., 2003; Wiliam, 2000). In a narrower view, formative assessment is considered as an important tool in instruction for regulating the students’ learning (Black and Wiliam, 2009). Formative assessment can help the students to adapt their learning process optimally (van Hattum-Janssen and Lourenço, 2006).

Butler and Winne’s (1995) model of feedback has been the basis of many derivatives in feedback research articles (Juwah et al., 2004; Nicol and Macfarlane-Dick, 2006). The Butler and Winne model had more than 600 citations as of September 2009 (Google Scholar, 2009), reflecting its relative importance. Juwah et al.’s (2004) derivative model of Butler and Winne (1995) is shown in Figure 2.4. A thoughtful look at the model shows the correlation with the feedback control system loop shown in Figure 2.3. Juwah et al. (2004) consider Sadler’s (1989) article as one of the strongest supporting studies of the importance of formative assessment and feedback. Sadler (1989) explains three important factors that students should take into consideration to benefit from feedback. These are: “The students must: *i*) Possess a concept of the goal/standards or reference level being aimed for; *ii*) Compare the actual (or current) level of performance with that goal or standard; and *iii*) Engage in

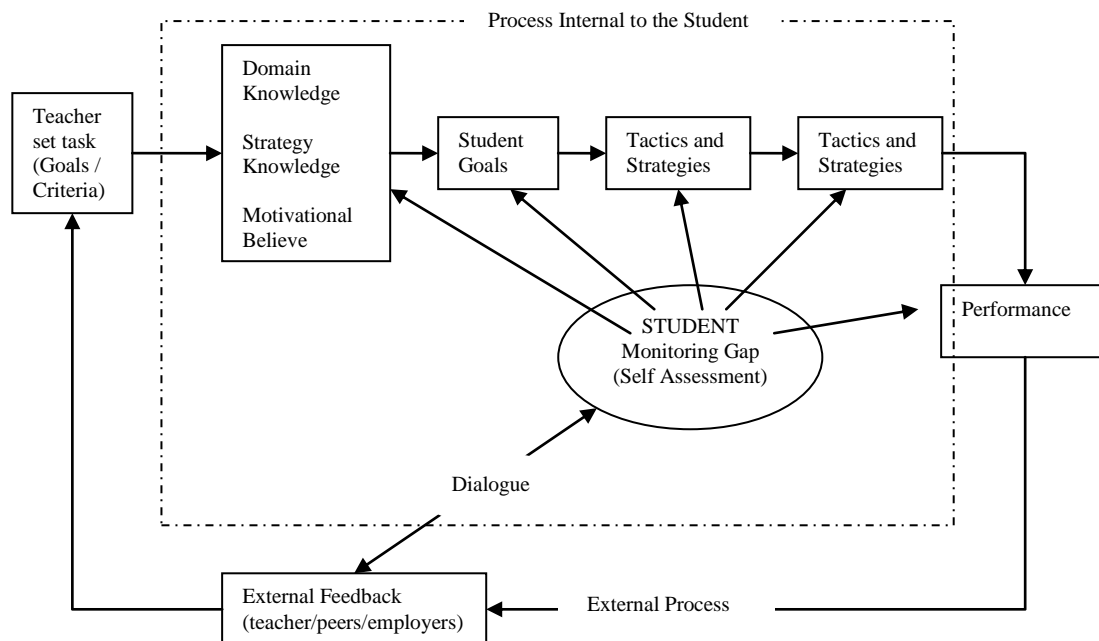


Figure 2.4. Model of formative assessment and feedback (Juwah et al., 2004).

appropriate action which leads to some closure of the gap”. The previous three factors are nothing else but a closed feedback control system loop.

Recent pedagogical research has increasingly emphasised the important role of enriching teaching with formative assessment practices and providing the students with more feedback. In its national student survey in 2005 and 2006, the Higher Education Funding Council for England (HEFCE) found that UK students were unsatisfied with feedback and assessment practices during the semester period (Race, 2005). In particular, students thought that they did not receive enough formative feedback about their actual learning level. Pedagogical research indicates that giving feedback is the most effective method that teachers can use to foster and maintain student learning, and emphasises that feedback must be provided promptly without delay (Race, 2005). This is very similar to control systems, where establishing rich and robust feedback is essential in designing stable systems that can meet their objectives (Goodwin et al., 2001; Åström and Murray, 2008).

Generally speaking, feedback and formative assessment pedagogical research share common concepts with control systems engineering. The next subsection introduces the self-regulated learning education research field.

2.5.3 Self-Regulated Learning Research

Self-Regulated Learning (SRL) is a relatively new pedagogical area that is closely related to control systems. Most SRL models and studies have emerged in the pedagogical and cognitive psychology society with no explicit link to studies in the control systems engineering society. The SRL term was first proposed in the mid-1980s (Zimmerman, 2008). Consequently, research studies were published defining the field further, proposing models and evaluation instruments and verifying through empirical research (Zimmerman and Martinez-Pons, 1986; Zimmerman and Martinez-Pons, 1988; Weinstein et al., 1987; Zimmerman, 1989; Butler and Winne, 1995; Pintrich et al., 1993; Pintrich, 2000; Boekaerts et al., 2000). SRL is defined as a “Proactive process that students use to acquire academic skills such as setting goals, selecting and deploying strategies, and self-monitoring one’s effectiveness, rather than as a reactive event that happens to students due to impersonal forces” (Zimmerman, 2008). Pintrich and Zusho (2002) define SRL as: “an active constructive process whereby learners set goals for their learning and monitor, regulate, and control their cognition, motivation, and behaviour, guided and constrained by their goals and the contextual features of the environment”. According to Hattie and Timperley (2007), SRL is a method by which the students “monitor, direct, and regulate actions towards the learning goal”. SRL is referred to as a constructivist process whereby students construct knowledge in autonomous ways (Paris and Byrnes, 1989). SRL is an inherently cyclic process (Zimmerman, 2000), very similar to the closed loop control system.

According to Borkowski et al. (2000), the emergence of SRL starts when children are guided on using learning strategies and matures when they can choose a suitable learning strategy and monitor and evaluate their learning process. Studies of the use of learning strategies have shown their impact on producing better learning outcomes (Zimmerman, 2008). Many research studies have shown that students who are greater self-regulating learners have utilised feedback more frequently, which has led to a better learning outcome (Pintrich et al., 1993; Zimmerman and Martinez-Pons, 1986). Butler and Winne (1995) assert that feedback is an inherent and essential element in the sub-processes that comprise the whole SRL process. Furthermore, feedback should assist the achievement of the goals of SRL. Nicol and Macfarlane-Dick (2006) argue that formative assessment can help students to become self-regulated learners. The more self-regulated the student is, the less demand for teacher support there is

(Zimmerman et al. 1996). It has been found that SRL skills can be generally learnt even by low-capability students (Pintrich and Zusho, 2002).

There are a few common and distinguishing components of SRL models: goal setting, learning strategies and monitoring and feedback. In comparison with the feedback control systems loop, shown in Figure 2.3, goals are the reference signals (setpoint), learning strategies are the controller, monitoring and feedback is measurement and feedback. The adoption of learning strategies is explicitly referred to as the *control component* of Pintrich's (2000) model of SRL. The model contains another three phases: forethought, monitoring and reflection. Puustinen and Pulkkinen (2001) conducted a review of SRL models that are emerging and empirically valid. They notice that SRL models are classified either as goal-oriented processes in the work of Zimmerman et al. (1996), Pintrich (2000) and Boekaerts et al. (2000), or as a process dominated by metacognition in the work of Borkowski et al. (2000) and Butler and Winne (1995). Indeed, if one looks at SRL from a control systems perspective, both goal orientation and metacognition are fairly important for the process to achieve its aim. Metacognition refers to the learners' ability to self-evaluate their progress and also to choose tactics and strategies that suit a learning or skill acquisition phase. This is relevant to the measurement, comparison, and controller components in the closed control loop system shown in Figure 2.3. If any of these components fail, the system will fail. Without a clear reference (goal), the process will lose its way, even if the other components are well designed and work properly. In principle, self-regulated learning can be viewed as a feedback control system loop where the student is responsible for establishing all of its components and signals.

A third pedagogical research area that correlates with engineering is instructional design which is introduced in the next subsection.

2.5.4 Instructional Design Research

The analogy between instructional design and engineering design can be found in several models. Instructional design is an established pedagogical discipline (Gagne et al., 2005) that is design oriented with guidelines to help people to learn (Reigeluth, 1999). In a review of instructional design models (ID), Gustafson and Branch (1997) state five essential elements of an ID model to be complete. The ID is implemented through the following stages: 'Analyse', 'Design', 'Develop', 'Evaluate' and 'Revision'. The elements are interrelated and

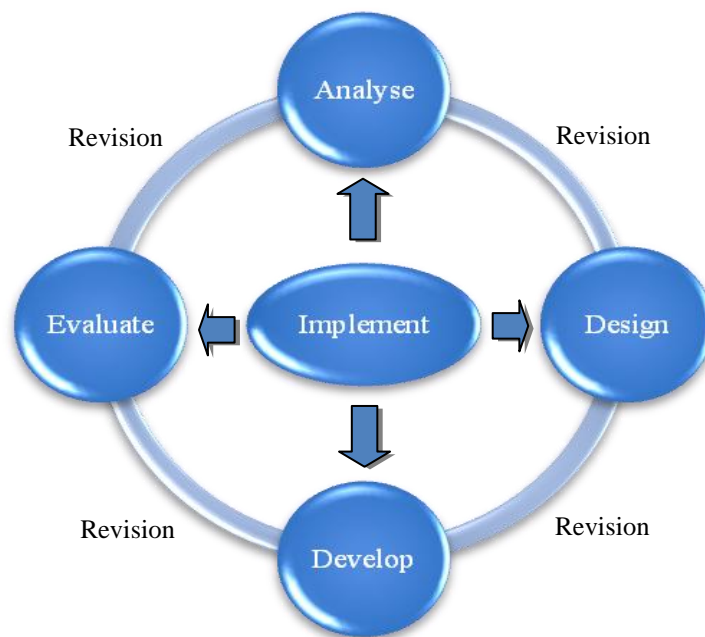


Figure 2.5. Instructional design cycle model proposed by Gustafson and Branch.

operate in an iterative dynamic cycle, such as that shown in Figure 2.5. This cycle is very similar to the control systems engineering design process.

The very early works on ID by Silvern (1965) used *Systems Theory* for proposing efficient instructional systems. The use of systems engineering principles for developing a holistic or microscopic approach of instruction can be found in the early works of John Dewey (1938) and Lewin (1942). A full body of research, called the Instructional Systems Development (ISD), has evolved as a result of using systems engineering concepts in instructional and learning design (Dick et al., 2001). The systematic design of instruction has been frequently considered as an effective way of enhancing learning production (Gagne and Briggs, 1979; Rothwell and Kazanas, 1997). Dick et al. (2001) propose a systemic model of instructional design in a frequently cited book. The model perceives instruction as a process composed of different interactive sub-systems and stresses the importance of the formative evaluation of each component of the system. A recent instructional design model that embraces the cyclic systemic structure can be found Ison et al. (2007).

There are instructional design models in the pedagogical literature that have been inspired by systems theory. However, very few have been proposed by researchers from the engineering or control systems society (Rompelman and Graaf, 2006).

2.6 Summary of Educational Theories

Behaviourism stress the observable character of learning, as it is a passive process shaped by stimuli (Slavin, 2005). Cognitivism has arisen as a response to behaviourism and emphasises that learning is an internal process that uses memory, motivation, thinking and reflection. Cognitivism perceives that learning pace and the level of gained knowledge is dependent on the processing capacity of the learner, the depth of processing, the processing channels, inference with other information and the learner's existing knowledge structure, referred to as schemas (Craik and Lockhart, 1972; Craik and Tulving, 1975; Clark and Paivio, 1991; Dempster and Corkill, 1999). Two to three decades ago, constructivism began to take considerable space in applied educational practices (Richardson, 2003). Constructivism emphasises experiential and authentic learning; it considers learning as a process by which learners transform complex information to make their own models (Kolb, 1984). Constructivism distinguishes itself from behaviourism by its emphasis on the processes of learning and the student-centred nature. Constructivists perceive learning as an active process and it is intrinsic in nature, while behaviourists perceive learning as a passive response to stimuli. Constructivism has been impacted by cognitivism (Hergenhahn and Olson, 2004); however, its approach is rather holistic, as opposed to the cognitivism emphasis on the internal mechanisms of learning. Kolb's experiential learning theory is one such example of the constructivist's view of learning as a process. The pedagogical theories, in particular constructivism and cognitivism, have inspired the development of different models of learning styles.

The dominant practices of teaching and learning in engineering education are expressed by the term "Chalk and Talk" (Mills and Treagust, 2003). The term refers to teaching and learning methods that have little pedagogical background. This can be related to the fact that engineering and science lecturers are very well trained in their domain of research but have seldom received any pedagogical training (Jarvis, 2001; Wankat et al., 2002). Learning theories can provide the background for designing enhanced engineering education models.

Behaviourism, cognitivism and constructivism are distinguished pedagogical schools, but there is a correlation between them in many aspects (Slavin, 2005). Engineering education design can benefit from each of these schools. However, constructivism seems to be more appealing for engineering education design because it emphasises aspects that are central for future engineering graduates. Such aspects include problem solving, communication skills, lifelong learning,

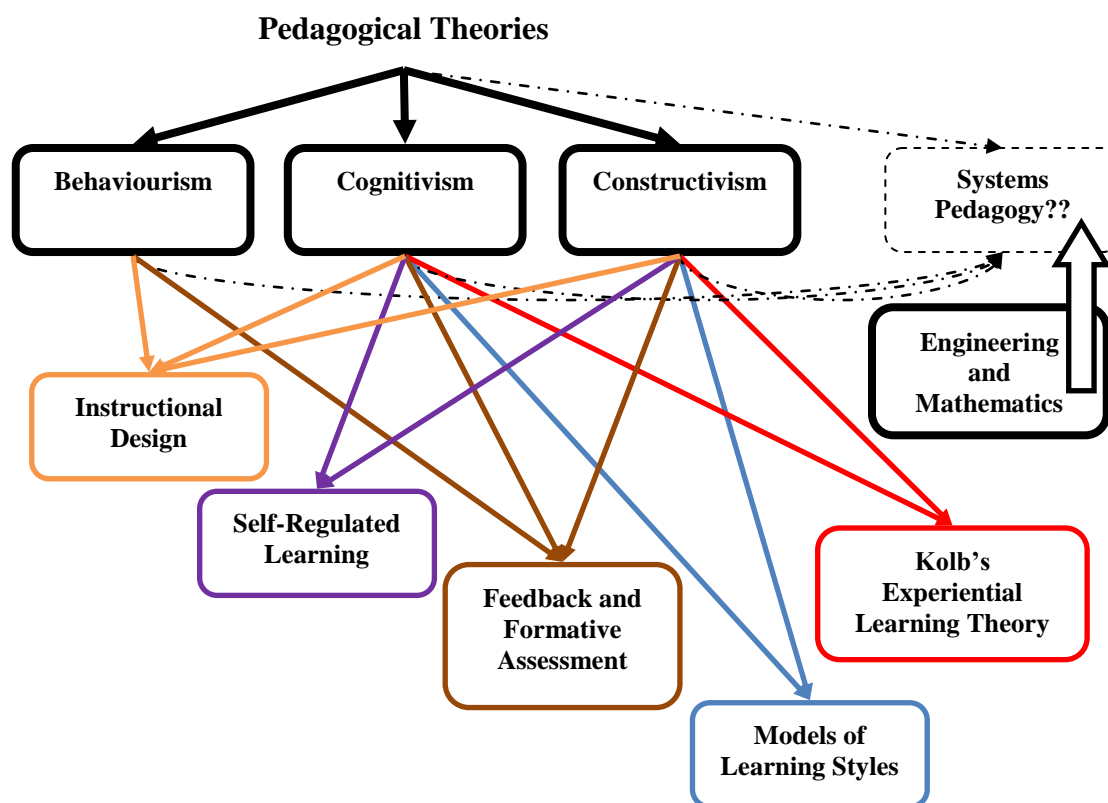


Figure 2.6. Diagram of the pedagogical theories presented in this chapter. The main schools are behaviourism, cognitivism and constructivism. Learning styles' models have their roots in the previous schools. Kolb's experiential learning theory is impacted by constructivism and cognitivism. Systems Pedagogy is a new paradigm which is proposed to integrate engineering and mathematics with pedagogy.

practical experience and holistic thinking etc. Constructivist approaches such as problem- and project-based learning (Blumenfeld et al., 1991; Polman, 1999; Thomas and San Rafael, 2000), self-regulated learning (Zimmerman, 2008), experiential learning (Kolb, 1984) and scaffolding (Vygotsky, 1978) could be very helpful in implementing the required skills of future engineering graduates.

Engineering, on the other hand, can have an impact on pedagogy. It has been shown that a number of educational research fields such as feedback and formative assessment, self-regulated learning and instructional design hold engineering concepts. Behaviourism may be perceived by means of *mathematical Game Theory* (Nash, 1951), where game theoretical models of learning design can be implemented in correlation with the behaviourist principles that were discussed in section 2.1. In our opinion, a holistic learning theory that unifies the pedagogical schools' thoughts would embrace constructivism as the outer framework for developing student-centred models of learning processes, utilise elements of behaviourism as a tool for enhanced regulation of these processes

and refer to cognitivism to inform the design process by understanding the involved internal cognitive and mental aspects. It is suggested later in this thesis (see Chapter 8) that a new pedagogical school of thoughts, namely ‘Systems Pedagogy’, could possibly emerge from the coupling of engineering, mathematics and pedagogy. Such a new theory could have a holistic view of pedagogy and would integrate findings from other educational theories with engineering and mathematical methods for designing enhanced teaching and learning processes. Figure 2.6 shows a diagram of the interrelationship between the different pedagogical aspects presented in this chapter and also shows the potential position of *Systems Pedagogy*.

2.7 Conclusions

This chapter has introduced briefly the mainstream pedagogical schools, such as behaviourism, cognitivism and constructivism. Considering educational theories is important during the design process of engineering education teaching and learning. Constructivism is the latest educational school; it emphasises many aspects that are relevant to engineering education. In particular, constructivist experiential learning theory is relevant to engineering and laboratory education because of the experiential nature of hands-on laboratories. Kolb’s experiential learning theory was described in detail, as it will be used as the basis of designing a new laboratory education model, with further details given in Chapter 6. Elements of cognitivism are used in Chapter 6 and Chapter 7 to explain some of the findings, and also in Chapter 8 during the course of the development of mathematical models of learning. It has been shown that many areas of educational research, such as feedback and formative assessment, self-regulated learning and instructional design, correlate with concepts from engineering (in particular from feedback control systems). It should be noted that the schools of educational theories overlap, and different aspects of each school can be useful in understanding empirical findings, for designing teaching and learning models and for analysing learning processes. A discussion of the interrelationship between educational theories has been provided. The next chapter provides a literature review of laboratory education.

Chapter 3.

LITERATURE REVIEW OF LABORATORIES

Overview

This chapter presents the literature review of laboratory education. It starts with an introductory section about the role of laboratories in engineering and science, followed by an explanation of their objectives and styles. In the subsequent sections, a review of the main modes of conducting laboratories, such as hands-on, virtual (simulated) and remote are presented. The advantages and disadvantages of each mode are analysed in conjunction with existing literature. An overview of the technologies used to implement virtual, hands-on and remote labs is provided with extended details of LabVIEW. This is followed by an overview of technologies of web portals development. The chapter ends by showing that the laboratory literature needs more empirical studies and concludes that hybrid labs have a high potential of being the most efficient way of conducting laboratory education.

3.1 Introduction

The central role of laboratory experience in engineering education curricula has been emphasised in a large number of science and engineering education articles (Dechsri et al., 1997; Johnstone and Al-Shuaili, 2001; Hofstein and Lunetta, 2004; Feisel and Rosa, 2005; Kirschner and Meester, 1988; Ma and Nickerson, 2006; Chu and Lu, 2008; Tan et al., 2000; Corter et al., 2004). Engineering had been taught as a pure hands-on subject until the 18th century. However, engineering education has benefited from the advances in science and it began to embed deeper theoretical concepts towards the end of the 19th century, especially in US higher education schools (Feisel and Rosa, 2005). Nevertheless, laboratory sessions and hands-on training remained much more important than theory and mathematics in engineering curricula until World War I (Wankat et al., 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 (Hofstein and Lunetta, 2004; Hofstein and Lunetta, 1982; Feisel and Peterson, 2002). Wankat (2004) observes that only 6% of the articles published in the *Journal of Engineering Education* from 1993-2002 had 'Laboratory' as a keyword. Laboratory pedagogy has recently been reported to be a fertile arena of research for the coming years (Hofstein and Lunetta, 2004; Feisel and Rosa, 2005), especially in the context of further utilisation of new developments in information and communication technology (ICT) for enhancing laboratory education.

3.2 Objectives of Laboratory Education

The literature regarding laboratory education shows close agreement of the objectives of laboratory education. Feisel and Rosa (2005) list many general objectives of laboratory education, such as relating theory with practice, motivating students and develop engineering sense. Hofstein and Lunetta (2004) state the following objectives of laboratory education: help the understanding of science concepts, develop interest and motivation, provide scientific practical skills and problem solving abilities, develop scientific habits, help the understanding of the nature of science, develop methods of scientific inquiry and reasoning, and help to illustrate the application of scientific knowledge to everyday life. ABET (Accreditation Board for Engineering and Technology), the main body for accrediting engineering subjects in the US, lists a set of thirteen important objectives of laboratory education: instrumentation, models, experiments, data analysis, design, learn from failure, creativity, psychomotor, safety, communication, teamwork, ethics in the lab and sensory awareness (Feisel and Peterson, 2002). Kirschener and Meester (1988) mapped over 100 objectives of laboratory education, which they found in the literature available until the mid 1980s, into eight main objectives: formulate hypotheses, solve problems, use knowledge and skills in unfamiliar situations, design simple experiments to test hypotheses, use laboratory skills in performing (simple) experiments, interpret experimental data, describe the experiments clearly and remember the central idea of an experiment over a significantly long period of time.

These objectives of labs are essential for providing engineers with skills for their future careers. Hence, one can understand the critical importance of laboratory education. Laboratory education can be conducted via different styles from structure or from access mode perspectives, and this is detailed in the next section.

3.3 Styles of Laboratories

Laboratories can be classified into two categories. The first category is concerned with the laboratory structure and the intended learning outcomes, e.g. the expository laboratory (Berg et al., 2003). The second category is based on the mode in which experiments are conducted, e.g. whether hands-on (Heise, 2006), remote (Nagy and Agachi, 2004) or virtual (Blanchard et al., 2006).

3.3.1 Styles of Laboratories from the Structure Perspective

Kirschener and Meester (1988) distinguish between four main types of lab: expository, experimental, divergent and stand-alone labs. The expository laboratory is a cookbook lab style. In this type of laboratory, the procedure is given in the form of a lab manual. The outcome of the experiment is predetermined and the students should follow the manual in a deductive way to obtain this outcome. Expository laboratories are used for didactic purposes, and they are the most widely used types in science and engineering undergraduate education (Johnstone and Al-Shuaili, 2001). The experimental or open-ended form (Berg et al., 2003) is an inductive, discovery oriented, unstructured project or undergraduate research project laboratory. Many Project Based Learning (PBL) assignments in engineering are conducted through this type of lab (Chu and Lu, 2008). The experimental laboratory is research oriented rather than being of a didactic nature. The divergent laboratory is a mix of expository and experimental labs. The stand-alone laboratory term is used to describe laboratory coursework that is independent and is not attached to any theoretical module.

3.3.2 Styles of Laboratories from the Access Mode Perspective

The classical form of conducting laboratory education involves the physical presence of the individual and the experimental rig. This is generally referred to as the **hands-on laboratory** in the literature (Ma and Nickerson, 2006). Hands-on labs are sometimes also called proximal labs (Lindsay, 2005). Recent advances in Information and Communication Technologies (ICT) during the last three decades have resulted in the emergence of two new modes of laboratory:

- **Virtual (Simulated) labs:** these are approximated simulations of a process of a physical experimental rig. Examples of virtual labs can be found in Karady et al. (2000a) and Blanchard et al. (2006).
- **Online (Remote) labs:** these are platforms that allow remote access to the physical experimental rig through the Internet or intranet. Examples

can be found in Aktan et al. (1996), Nagy and Agachi (2004), Arpaia et al. (2000), Bauchspiess et al. (2003) and Callaghan et al. (2008).

The Loughborough Process Control Lab, which is the main case study of this thesis, is of an expository nature. Virtual and remote access modes have been developed and utilised in association with the hands-on lab during the teaching and learning process in the Chemical Engineering Department of Loughborough University. Further details are shown in Chapters 4, 5, 6 and 7. Figure 3.1 shows a conceptual model of the style of the Loughborough Process Control Lab. The next sections provide a review of hands-on, virtual and remote laboratories.

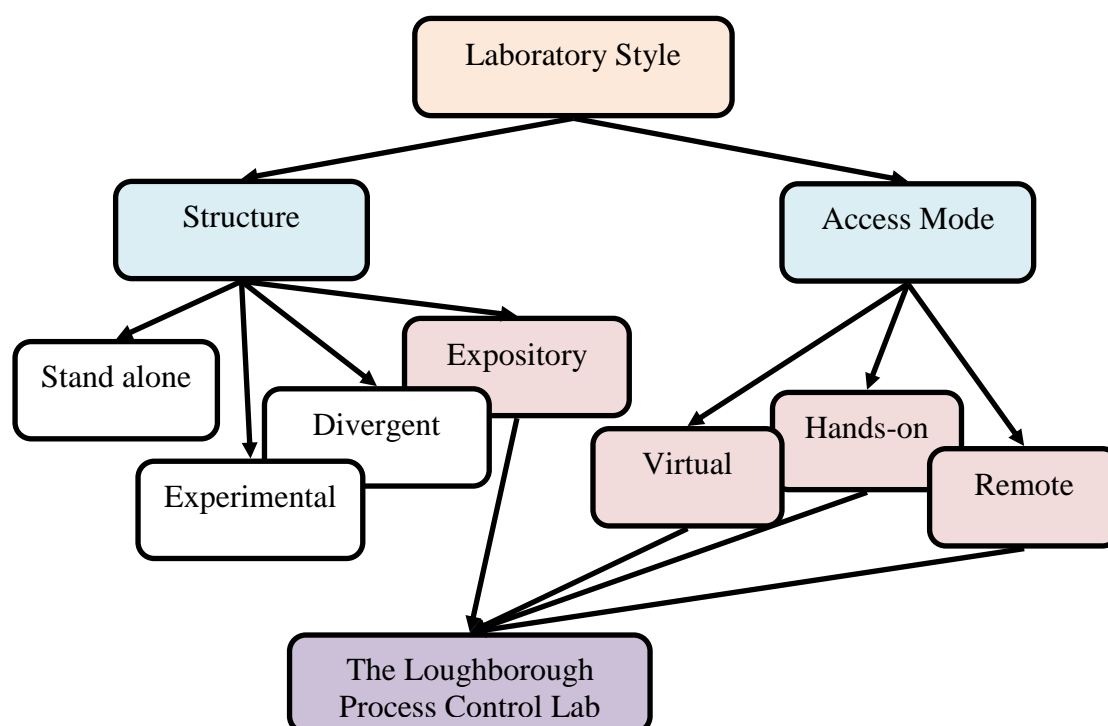


Figure 3.1. The Loughborough Process Control Lab in relation to the style of laboratory from the structure and access mode perspectives. The lab is of an expository nature and the virtual, hands-on and remote access modes of the lab have been utilised.

3.4 Hands-on Laboratories

In this section, an overview of reports in the literature of the importance and constraints of hands-on laboratories is given.

3.4.1 Why are Hands-on Laboratories Important?

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. The absence of realism may serve as a demotivating factor in the learning process. Many studies relate the significantly higher order learning or behaviour in real settings vs. virtual settings to the realism factor (de Kort et al., 2003; Heise, 2006). Witmer et al. (1996) state that better learning and training requires a higher level of fidelity and realism. The constructivist pedagogy literature frequently emphasises 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.

3.4.2 Constraints of Hands-on Laboratories

Constructing knowledge is a complex process that can be out of the time frame of the planned hands-on laboratory sessions. For instance, constructing knowledge has four main phases, according to Kolb's experiential learning theory, which include stimulation, reflection, abstraction and experimentation (Kolb, 1984). Educationalists consider learning as an iterative process (Papert, 1980; Kolb, 1984; Hmelo et al., 2000). Meaningful learning in laboratories does need reflection (Hofestein and Lunetta, 2004). These practices are generally missing in the classical teaching of hands-on laboratories, mainly due to time constraints. 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 demonstration (Kolb, 1984). The aimed impact of laboratory education on the students' learning is often not realised (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. This drawback has been frequently reported in laboratory literature (Johnstone and Al-Shuaili, 2001; Hofestein and Lunetta, 2004; Ma and Nickerson, 2006).

In brief, hands-on laboratories suffer from many limitations, such as time constraints, poor knowledge construction (Kirschner and Meester; 1988;

Gunstone, 1991; Roth, 1994), only one demonstration in most cases, material consumption, technical defections, expensive equipment, hazardous operation, (e.g. high-voltage power lab), the need for the presence of one or more tutors or/and technicians, and constraints on physical allocation.

3.5 Virtual (Simulated) Laboratories

Virtual labs are computer simulations of laboratory processes. In the literature, the term sometimes refers to remote labs (Guimaraes et al., 2003); however, in this thesis, a virtual lab strictly refers to a computer simulation, while the term 'remote lab' or 'online lab' is used to refer to a remotely controlled physical rig.

3.5.1 Historical Perspective

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). The idea of fostering the utilisation of simulations for training purposes in the US can be attributed to the seminal work of Engelbart (1962), who proposed developing computer systems to assist in training issues.

During 1968, an interactive simulation system of the medical management of patients with hypertension was developed at the University of Alberta, Canada (Hunka and Buck, 1992). In parallel, 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 et al., 1977). The positive impact of using computer simulations on students' learning has been reported in the literature since then.

3.5.2 Impact of Computer Simulations on Students' Learning

Computer simulations became an integrated part of engineering education as early as the 1970s (Nagel, 1975; Hites et al., 1999; Campbell, 1985; Gladwin et al., 1992; Gosman et al., 1977; Ingram et al., 1979; Kinzel et al., 1981; Laghari et al.,

1990; Smith, 1976; Prigozy, 1989; Chamas and Nokali, 2004). Sometimes, virtual labs have replaced the use of hands-on laboratories (Gonzalez and Musa, 2005). Many research papers report a positive impact of computer simulations on students' learning (Kinzel et al., 1981; Adams, 1981; Campbell, 1985; Laghari et al., 1990; Shute and Grendell, 1994; Tjaden and Dianne, 1995; Jimoyiannis and Komis, 2001).

In 1977, Computer Aided Design (CAD) was integrated into design courses at Ohio State University, resulting in a greater workload. However, the students had a surprisingly positive attitude towards this extra workload (Kinzel et al., 1981). Kinematics computer simulations for undergraduate mechanical engineering students were found to be useful in deepening the students' conceptual understanding (Adams, 1981). Interactive simulation software was used in an undergraduate digital signal processing course at Paisley Institute of Technology in Scotland. The software was reported to be very beneficial for students learning (Campbell, 1985).

Shute and Grendell's (1994) study of a statistics course found that computerised learning gives equal or even better conceptual understanding than traditional textbook-based learning. The students considered learning with the interactive software more enjoyable and helpful than the classical textbook, paper and pencil method. Similar results were reported by Tjaden and Dianne (1995). A positive impact of simulation on conceptual understanding was found in a case study of using computer simulation in physics (Jimoyiannis and Komis, 2001).

3.5.3 Advantages of Computer Simulations and Virtual Labs

Computer simulations or virtual labs have brought many benefits for engineering and science education. In their survey paper, Gladwin et al. (1992) enumerate many advantages of computer simulations in chemistry, 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 et al., 2002). This is in correlation in particular with Kolb's 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 et al., 1995). Virtual labs are available any time (McAteer et al., 1996; Dobson et al., 1995). 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 and Musa, 2005; McAteer et al., 1996). The pressure related to the costs of building and running hands-on labs has often led to replacing them with virtual labs (Magin and Kanapathipillai, 2000). With virtual labs, students are not restricted by affective feelings such as fear of damaging equipment or components. It has been found that virtual labs encourage experimentation in a form which did not take place in a laboratory where real components were used (Dobson et al., 1995). Using animals can be avoided by utilizing virtual labs in bioscience (McAteer et al., 1996). Distance learning courses can benefit from virtual labs (Eckhoff et al., 2002; Blanchard et al., 2006).

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.

3.5.4 Disadvantages of Computer Simulations and Virtual Labs

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 recognise 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 et al., 2003; Magin and Kanapathipillai, 2000; Ma and Nickerson, 2006;

McAteer et al., 1996; Raineri, 2001; Ronen and Eliahu, 2000; Spicer and Stratford, 2001). Yet virtual labs can be effective assisting tools, whether offered online or as independent digital applications to be run on personal computers.

3.6 Remote (Online) Laboratories

The evolution of the Internet and networking technology has left a growing impact on the laboratory and experimentation philosophy. In this section, a snapshot is given of the new evolving form of laboratory education, called the *online or remote laboratory*.

3.6.1 Historical Perspective

The idea of implementing labs through the Internet for educational purposes can be traced back to the early 1990s, when Aburdene et al. (1991) suggested a futuristic solution for sharing laboratory equipment through the Internet. They expected that this model would be used for operating experiments in the classroom and by other partner institutes. They envisaged that this model would initiate new pedagogical opportunities and research and effectively foster collaboration between institutes. Most features of the model they proposed were consequently implemented by others within a few years.

Table 3.1. Selected list of some online laboratories in different continents.

Online Lab	Brief Description	Country
MIT iLab	The remote lab hub of Massachusetts Institute of Technology	USA
	http://ilab.mit.edu/ServiceBroker/	
NUS Internet Remote Experimentation	Remote laboratories from the National University of Singapore.	Singapore
	vlab.ee.nus.edu.sg/intr.html#robot	
KTH Online Remote Laboratories	Remote labs in power and energy from the Royal Institute of Technology in Sweden	Sweden
	http://www.energy.kth.se/proj/projects/remote_labs/	
UTS Remote Labs	Remote labs from the University of Technology, Sydney.	Australia
	http://remotelabs.eng.uts.edu.au/	

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, as shown in Table 3.1, which includes representative examples from each continent. The next two subsections detail over the advantages and disadvantages of remote labs.

3.6.2 Advantages of Remote Laboratories

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). 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. Indeed, during the 1970s and 80s, this led to a move among the institutions administrators to minimise laboratory work in the undergraduate curricula (Kirschner and Meester, 1988). The idea of sharing experimental resources for cost minimisation can be traced to the early 1990s (Kondraske et al., 1993). This potential has been reported many times since then (Ogot et al., 2002; Ma and Nickerson, 2006; Callaghan et al., 2008). In Australia, a project currently under development aims to share remote experiments on a nationwide scale (LabShare, 2010).

It has been reported in many papers that online laboratories have stimulated the students' enthusiasm towards the studied subject (Aktan et al., 1996; Ma and Nickerson, 2006). Online labs may accommodate different learning styles (Eckhoff et al., 2002). They can enhance the outreach of distance learning courses in engineering (Salzmann et al., 2000; Eckhoff et al., 2002; Ogot et al., 2002; Bourne et al., 2005). 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).

3.6.3 Disadvantages of Remote Laboratories

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 (Srinivasagupta and Babu, 2003; Ogot et al., 2002). 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 et al., 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.

3.6.4 Technologies of Implementing Remote Laboratories

The easiest way to implement a remote lab is by using a remote desktop application (Salzmann et al., 2000). One such implementation can be found in Callaghan et al. (2008), however this is not a very practical approach since remote desktop applications send the server screen to the client pixel by pixel, while only a set of these is needed (Salzmann et al., 2000). Many other different IT tools have been used for implementing online laboratories. Matlab/Simulink and the real time Linux operating system were used to implement the remote inverted pendulum experiment (Garcia et al., 2002). Matlab/Simulink was also reported to be the implementation tool of Casini et al. (2003) and Swamy et al. (2000). Mobile robotics experiments were implemented using the open standards of Web technologies such as HTTP (Hypertext Transfer Protocol), HTML (Hyper Text Markup Language), XML (Extensible Markup Language) and Java (Guimaraes et al., 2003; Chang et al., 2006). LabVIEW (Travis and King, 2007) was reported as an implementation tool for many online labs in Ertugul's (2000) survey paper. Many other research papers also reported LabVIEW-based remote labs (Nagy and Agachi, 2004; Eckhoff et al., 2002; Hercog et al., 2007; Callaghan et al., 2008; Stefanovic et al., 2009). LabVIEW has been a favoured solution for implementing remote labs, as well as virtual and hands-on labs. Further details are provided in the next section.

3.7 LabVIEW as an Integrated Environment for Implementing Virtual, Hands-on and Remote Labs

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) was developed by National Instruments (www.ni.com) in the early 1980s with the vision of building an effective programming tool that reduces the time required to develop instrumentation systems software (Travis and King, 2007). The first version of LabVIEW was released in 1986 (National Instruments, 2009), however it has developed much beyond the initial release. Nowadays, LabVIEW presents a platform for combining many software tools for implementing complex virtual labs, simulations, acquisition and interfacing with physical rigs, and implementing remote operations through the Internet (Travis and King, 2007). LabVIEW has been reported frequently in the literature as a tool for implementing virtual, remote or hands-on labs in academia (Salzmann et al., 2000; Ertugul, 2000; Tebbe, 2006).

LabVIEW is a suitable and cost-effective tool for implementing laboratory applications (Salzmann et al., 2000; Trevelyan, 2002; Ertugul, 2000). An example of a virtual lab for a refrigeration experiment implemented in LabVIEW can be found in Tebbe (2006). Choi et al. (2000) used LabVIEW as an effective tool for teaching a mechatronics course. Eckhoff et al. (2002) used LabVIEW for developing a remote control for a smart truss bridge rig offered for a class on smart materials and sensors. Salzmann et al. (2000) used LabVIEW as the main tool for developing PID control engineering remote experiments. Lauterburg (2001) enumerates several examples in which LabVIEW simulations have been effectively used in teaching physics in a classroom setting or in the lab, such as tracking motions with a laser distance sensor, the demonstration and analysis of heat conduction and visualizing acoustic signals. Many other examples of using LabVIEW for engineering laboratory education can be found in Ertugul (2000), Tan et al. (2000), Trevelyan (2002), Eckhoff et al. (2002), Hercog et al. (2007), Callaghan et al. (2008) and Stefanovic et al. (2009). LabVIEW has been reported as a more suitable programming environment for engineering students than textual programming languages such as C or Java (Trevelyan, 2002; Moriarty et al., 2003).

The market responses indicate that LabVIEW is one of the primary choices in designing control and analysis solutions in the area of technology and education (Ertugul, 2000). Trevelyan (2004) states that LabVIEW is particularly superior for deploying remote labs than other programming tools because of its excellent Internet connectivity tools, its support of a wide range of industrial hardware, its

multiplatform support, its application building capability and for being commonly used in academia.

The positive attitude towards LabVIEW in the laboratory education literature can be related to the following factors:

- LabVIEW initially started as a high quality software platform for data acquisition.
- LabVIEW is inherently a Virtual Instrumentation (VI) development environment. Its codes and files are called VIs. The virtual instrumentation concept facilitates building effective and compact laboratory experimental interfaces (both functionally and from the user interface perspective).
- LabVIEW offers a comprehensive library for measurements, filtering and data analysis.
- LabVIEW offers the possibility of implementing simulations for a wide spectrum of engineering problems. LabVIEW toolkits offer a very comprehensive set of already implemented functions.
- LabVIEW has embedded Internet connectivity tools that enable web deployment of LabVIEW Virtual Instruments (VIs).
- LabVIEW has many connectivity tools that enable the importing of other engineering files, e.g. Matlab/Simulink codes or Solidwork 3D models. This is particularly an enabler for using legacy codes.
- LabVIEW also has connectivity tools with other applications such as MS Office or SQL database.
- LabVIEW codes are called 'G-code' since LabVIEW is a graphical programming environment. The G-code is more appealing for engineers than text-based programming. With G, programming is done through drag and drop graphical functions instead of line text. However, programmers who are used to textual programming find difficulty in using LabVIEW, at least initially.
- LabVIEW offers a software application development kit that enables the creation of standalone executable applications from LabVIEW VIs, similar to other programming languages such as Visual C++ or Visual Basic.

- In LabVIEW, an interaction with data is performed through a professional Graphical User Interface (GUI) that would include controls, graphs and 3D visualisation tools.
- LabVIEW offers many embedded solutions for Internet publishing.
- LabVIEW offers multimedia connectivity where audio/video files can be embedded in the developed application.
- LabVIEW has an active collaborative community and a large number of reusable legacy codes.

These features and others have made LabVIEW a favoured platform for implementing virtual and/or remote labs and interfacing with hands-on labs. Further details of the LabVIEW programming environment and Internet connectivity are provided in Chapter 5 and Appendix 12. Details of how LabVIEW has been used to implement virtual, hands-on and remote access to the Loughborough Process Control Lab are also shown in Chapter 5.

3.8 Developing a Web Portal for a Remote Laboratory

The core remote lab connectivity can be developed with LabVIEW or other remote lab construction technology. However, a dedicated online portal will be required to publish the remote lab in a professional effective way. This section details the available technologies for web development.

3.8.1 Web Development Tools

In the early days of the Internet, online publishers used to type an HTML/XHTML (Extensible Hypertext Markup Language) code into text editing software to generate online web pages (Altheim and McCarron, 2000). With HTML, pages largely consisted of static text, links and a limited amount of graphics. Some of the frequent disadvantages of developing HTML pages are the difficulty of producing a neat HTML code, broken tables, links without reference, lost graphics and poor quality content presentation (McKeever, 2003). The process is exhaustive and requires comprehensive programming knowledge of HTML. Since a knowledgeable person is always needed to develop and deploy HTML-based websites, this has been normally referred to as the *Webmaster Model* (Yu, 2005). The model has proved to be inefficient since it lacks the flexibility and scalability needed for managing the increased complexity demands on websites (McKeever, 2003; Yu, 2005). Later on, web authoring tools such as FrontPage and Dreamweaver have been developed to ease the process of creating web

pages, enabling novices with a modest knowledge of HTML to develop online content. However, for large, complex, multimedia rich and dynamic websites, web authoring tools still have their inherent constraints.

The third generation of web publishing, the so-called web content management systems (WCMS), emerged later, and currently provides the state-of-the-art solution to professional web publishing. WCMSs are used as an alternative to web authoring tools when there is a need to build complex and dynamic websites (Sunny, 2008). Although WCMSs have been around for a while, their popularity as tools for developing complex and dynamic websites is recent (Yu, 2005). In the next subsections, further details about web content management systems and their usage in academia are provided.

3.8.2 Web Content Management Systems

A web content management system (WCMS or Web CMS) is content management system (CMS) software, which is usually implemented as a Web application, for creating and managing HTML content. It is used to manage and control a large, dynamic collection of web material (Yu, 2005). In contrast with web development tools such as HTML, FrontPage, Dreamweaver etc., a WCMS facilitates the development of more complex features, cost effectiveness and online flexibility (McKeever, 2003; Powell et al., 2003; Yu, 2005; Souer et al., 2008). Using WCMSs helps organisations to manage complex emerging websites with a high quality appearance (Boiko, 2001). The life cycle of website development with a WCMS includes two phases: content collection and content delivery or publishing (McKeever, 2003). Content such as text, graphics, video and audio is collected and stored in a repository. Then the delivery phase extracts the content and publishes it for the World Wide Web. This is a very difficult and time-consuming process in a non-automated environment, such as when developing with HTML or FrontPage (McKeever, 2003). It is argued that WCMS provides a solution for overcoming problems associated with the usage of today's data-intensive web applications such as consistency, navigation, content audit and control, tracking of content and data duplication (Vidgen et al., 2001). There are commercial and free open-source WCMSs available in the market. The main superior feature of open source WCMSs is the community of developers. A popular web content management system has a community of many hundreds, or even thousands, of developers. This community works on enhancing the code, releasing new versions, solving bugs and building new features for extending the WCMS functionality.

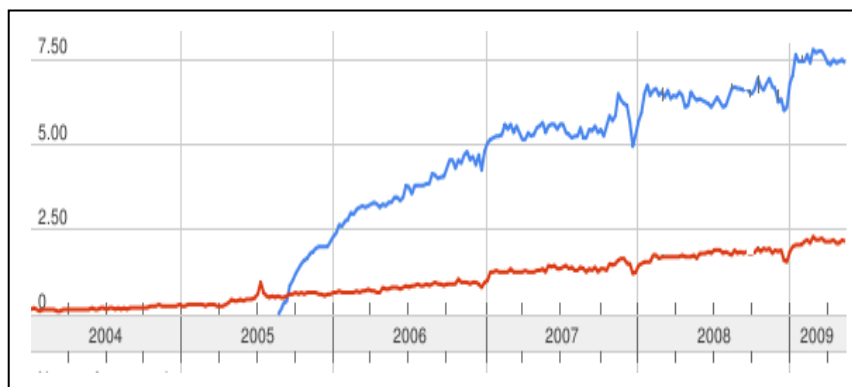


Figure 3.2. Joomla (Blue, 3.5) vs. Drupal (Red, 1.0) search rates from Google Trends

Currently, there are many available systems for web content management, both commercial and open source. For this project, it was aimed to adopt the open source choice to avoid any further costs, especially as many of the open source CMS such as Joomla (2009) and Drupal (2009) have equivalent features to commercial systems (LeBlanc, 2007). Both Joomla and Drupal were classified as 1st and/or 2nd winners of the Open Source CMS Award for the years 2006, 2007 and 2008 (Packt Publishing Awards, 2009).

Drupal is particularly useful for developing online websites that contain social networking features and Web 2.0 applications. On the other hand, Joomla is more suitable for the portal type websites, yet can be equipped with social networking capabilities. Joomla has been reported to be the used tool for building social networking websites (Yue et al., 2009). Joomla is more popular than Drupal, as shown in Figure 3.2. The presented data is taken from Google Trends and reflects the Internet keyword search ratio of Joomla vs. Drupal (Google Trends, 2009). The data shows that the users' propensity to search for Joomla is 3.5 higher than searching for Drupal.

3.8.3 The Use of Web Content Management Systems in Academia

Using WCMSs for academic purposes is very recent; however, it is expected to become more popular in the near future. Joomla and Drupal seem to be the most preferred web content management systems used in implementing websites or developing new applications in academia (Samarawickrema, 2007; Shida et al., 2007; Klimeck et al., 2008; Obonyo and Wu, 2008; Rutherford and Figg, 2009; Young and Archambault, 2009). For example, Drupal was used to build a website for supporting blended learning in a graduate course about principles and novel issues in education technology at Utah State University in the US (Holton, 2009).

Drupal was used for building a learning network at Brock University in Canada for facilitating the staff and students networking at the faculty of education (Rutherford and Figg, 2009). Different content management systems, particularly Drupal, were used at the college of education, University of Nevada, Las Vegas, for managing and developing web content (Young and Archambault, 2009).

Joomla was used for developing a website for second-year undergraduate students in the education department at Deakin University in Australia as a medium to collaborate within groups and also to practise online teaching. It was also used for the Business and Law Faculty staff and students for research and teaching (Samarawickrema, 2007). Joomla was used for developing a website for connecting astronomy activities for the public (Shida et al., 2007). Joomla was used for building a website for the Network for Computational Nanotechnology, a US National Science Foundation established network between universities for supporting the national nanotechnology initiative (Klimeck et al., 2008). Through its website, nanoUUB.org, tens of thousands of users from 172 countries collaborate in solving problems and sharing knowledge related to nanotechnology. Joomla was used for building a web-based knowledge forum for facilitating the creation of a professional community to support international research among spatially distributed students in the field of building construction at the University of Florida in the US (Obonyo and Wu, 2008). Joomla was extended and augmented with Mathematica to develop an intelligent mathematics quiz generator based on the Bayesian Networks' estimation of students' progress (Driouech and Park, 2008).

Since Joomla is an open source WCMS, it was used as the core basis for developing an e-Portfolio system for students of Portsmouth University to present themselves online. The system is multi-user and each student's portfolio has sections such as an introduction, academic/career progress, CV etc., (Williams, 2007). The system was developed with PHP and made extensive use of the Joomla Database architecture. Williams (2007) enumerates a number of benefits of programming applications based on the Joomla open source extension, such as the use of the advanced user registration and login capabilities, customisation flexibility and the extensive list of available third-party extensions ready to plug -in to improve the website features. All these extensions can run on a Joomla website, but only a single database, a template and the Joomla core need to be maintained. When a programmer builds a Joomla extension with PHP, it will inherit the look and feel of the whole website. One

very interesting characteristic of developing Joomla extensions is the portability. Any extension developed for Joomla will be portable and can be installed on any Joomla-based website so that others can use a newly programmed component without the need for knowledge of programming or data-base configuration.

Joomla was adopted as the solution for building an online remote laboratory portal together with LabVIEW, as shown in Chapter 5. This is probably the first time that Joomla is augmented with LabVIEW to provide a full solution to remote laboratory dissemination.

3.9 *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, in an investigation into the effectiveness of a remote laboratory, it has been quantitatively found that remote students achieved about 5% to 8% fewer learning outcomes than the hands-on students, and they also needed more time to finish the experiments (Sicker et al., 2005). On the other hand, other researchers report contrary results (Corter et al., 2004; Lang et al., 2007). Corter et al. (2004), in their comparative study of online versus hands-on labs, found that most students rate the remote lab equal to, or even better than, the hands-on lab. The quantitative investigation of students' lab exam scores also reveals similar or better results for remote students. Lang et al. (2007) also found that conducting experiments via the Internet is equally successful to conducting them in the hands-on laboratory.

Heise (2006) conducted a comparative study of students' performance in a digital logic lab, which was offered as a hands-on and a simulated version. Heise observed that the students' motivation, interest and scores when using the hands-on lab increased significantly compared to the simulated labs. Heise also mentions that his colleagues at other institutes have made similar observations related to the superiority of physical labs compared to simulated labs.

Tzafestas et al. (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.

There is a consensus among many researchers that virtual labs should be used as supplementary activity and not as a replacement for hands-on labs (Engum et al.,

2003; Raineri, 2001; Ronen and Eliahu, 2000; Spicer and Stratford, 2001; McAteer et al., 1996). Engum et al. (2003) made a comparative study of using a virtual catheter lab versus a real catheter lab. The study revealed that both categories of students were adequate in demonstrating the aimed skills. However, the students preferred performing in the real lab compared to the virtual lab. Engum et al. (2003) suggests that: *“a combination of the two methodologies may enhance the students’ satisfaction and skills acquisition level”*.

Raineri (2001) supplemented her hands-on laboratory in molecular biology with a simulated version that runs on the web. The main aim of the simulated lab is to provide the students with the possibility of repeating the experiments many times so that they can acquire skills in techniques, data manipulation and interpretation that are very difficult to acquire during the usual three-hour classical hands-on laboratory session. Using the simulated lab with the course over five years yielded a 5% increase in the final exam scores, and a dramatic decrease in the number of students who either failed or passed only at the minimum threshold. Raineri stresses the importance of the hands-on lab, and that the simulated lab is rather a supplementary yet important addition to the module. Nevertheless, the students’ improvement as a result of using the virtual lab could be confounded by the fact that the lecturer may have gained much more experience in teaching the course after five years.

Similar outcomes and conclusions can be found in Ronen and Eliahu’s (2000) study. They used computer simulation software to offer a supplemental mimicking version of an electrical circuit design experiment. They found that 70% of the students in the experimental group benefited from using the simulation. The virtual lab enhanced their confidence, helped maintain their patience when working on the assigned task and played a significant role as a constructivist feedback instrument. The students who did not benefit from the simulations were either those with very high conceptual capabilities and so the software provided no additional aid for them in the task, or those with a very low understanding of the domain and showed no interest in improving. Ronen and Eliahu (2000) pointed out that simulations are only important supplements to the hands-on lab and not in any way an alternative.

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 utilised before or after the real field trip.

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. Both modes are important and they are not mutually exclusive (McAteer et al., 1996).

Lindsay (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. Hofestein and Lunetta (2004) call for enhancing laboratory education by adopting further ICT. Ma and Nickerson (2006) emphasise 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 (Raineri, 2001; Engum et al., 2003; Tzafestas et al., 2006), with findings consistently indicating the advantages of hybrid structures. However, reports in the literature of hybrid labs that utilise hands-on, simulated and remote modes in one stand-alone complementary package are scarce.

3.10 Pedagogy and Empirical Studies in the Laboratory Education Literature

A thorough literature review of engineering laboratory design, particularly in the context of incorporating new technologies such as virtual and/or remote labs, reveals that the majority of articles are technically focused. Most of those papers lack pedagogically informed design, and only a small percentage provides a quantitative evaluation of the educational effectiveness. For instance, Ma and Nickerson (2006) conducted a comprehensive literature review of simulated, hands-on and remote labs. Their literature research methodology concentrated on searching through ACM, IEEE and ScienceDirect web data-bases. They also surveyed the tables of content of educational journals that publish articles about laboratory education, such as *Computer and Education*, *Computers in Human Behaviour*, the *Journal of Learning Sciences*, *Learning and Instruction*, the *International Journal of Electrical Engineering Education*, and the *International Journal of Engineering Education*. Out of the 1000 articles found in this research, filtering with particular emphasis on those which have some educational content and not purely technical details, only 60 articles were identified for a full reading. *This indicates that about 6% of laboratory articles have some relation to pedagogy and/or contain empirical findings.* There were 20 articles with a relationship with

hands-on labs, 20 articles with a relationship with simulated labs, and 20 articles with a relationship with remote labs. These articles are tabled in Appendix 1.

To evaluate the extent of the educational content of these filtered articles, they were surveyed by the author of this thesis, who could access 40 out of 60. In total, 12 out of 20 of the hands-on lab articles, 3 out of 20 of the simulated lab articles and 5 out of 20 of the remote lab articles could not be accessed. Those articles that have been surveyed show that seven of the hands-on lab related papers are pedagogically centred studies, and the last one (Elton, 1983) is concerned with the economy of laboratory education. However, the picture was very different when it came to the articles of simulated and remote labs. It was found that the majority of these articles, 24 out of 32, are technically focused with some limited educational content. The reported pedagogy has been rather a brief qualitative discussion of constraints and educational objectives. There have been only two pedagogically centred articles with emphasis on design (Shin et al., 2002; Edleson et al., 1999), five articles that involve educational evaluation (Edward, 1996; Dobson et al., 1995; McAteer et al., 1996; Scanlon et al., 2004; Thakkar et al., 2000) and one article that discusses cognitive issues with imaginary experimentation in the mind (Raineri, 2001). None of the 40 articles on simulated or remote labs in Ma and Nickerson's (2006) review involve empirical evaluation with quantitative variance-based methods. No article shows a design model of hybrid combinations of the three modes.

Ma and Nickerson's (2006) review is by no means an inclusive one; however, it presents an interesting sample of recent literature of laboratory education. The lack of pedagogically centred or empirical investigations of simulated and remote labs compared to the hands-on lab can be related to the fact that the first two are rather new forms. In this thesis, a new approach for laboratory education is described. This approach integrates elements of virtual, hands-on and remote labs and is solely underpinned by Kolb's experiential learning theory (Kolb, 1984) with a comprehensive empirical quantitative analysis; see Chapters 5, 6 and 7.

3.11 Conclusions

The important role of the laboratory in engineering and science education has been frequently emphasised 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. A literature review of LabVIEW as a universal platform for implementing virtual, hands-on and remote labs has been provided. This is followed by a section on the technologies of web portal development, showing that Joomla is a very suitable option. It has been shown that there is a shortage of empirical studies in the laboratory literature. 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. In the next chapter, the case of Loughborough Process Control Lab is presented, followed by a chapter on developing a hybrid laboratory structure with LabVIEW and Joomla.

Chapter 4.

THE LOUGHBOROUGH PROCESS CONTROL LAB

Overview

This chapter introduces the Loughborough Process Control Laboratory. The lab has served as a test bed for the technical development and pedagogical investigations of the subsequent chapters of this thesis. The lab consists of six pilot scale rigs and one modular rig. The components of the rigs are described and the main concept of the lab such as instrumentation, PID control and tuning, are introduced. The lab was initially designed to be a compulsory part of second year courses at the Chemical Engineering Department of Loughborough University, but it has been utilised in other courses, too. Detailed description of the experimental procedures of the laboratory sessions for the undergraduate courses is presented and is followed by concluding remarks.

4.1 Introduction to the Loughborough Process Control Laboratory

The Process Control Laboratory of the Chemical Engineering Department at Loughborough University was implemented in 2005. The lab aims to support process control engineering education in undergraduate and postgraduate courses in the department. The lab has been mainly used in the second year courses CGB006-Instrumentation, Control and Industrial Practice for BSc students, CGB014 – Instrumentation, Control and Industrial Practice for MEng students, and CGB914 - Instrumentation and Control for BEng students. In addition, it has been used in the first year course CGA007- Process Balances for MEng and BEng students and in the postgraduate course CGP075 - 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 experiment plus a number of other different process control demonstrations. The experimental procedures of the

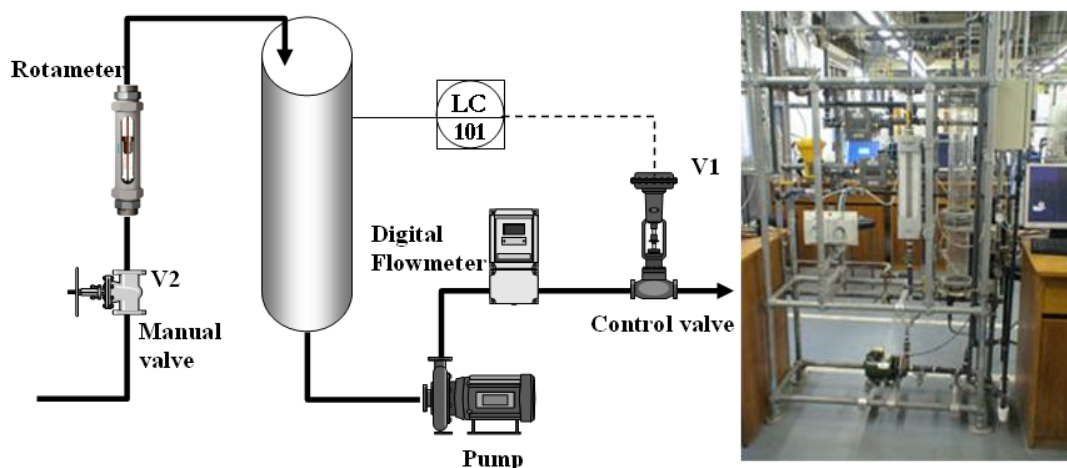


Figure 4.1. Schematic diagram of the pilot scale rig (left) and a picture of one of the experimental rigs (right).

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 lab was established with the vision of supplementing it with virtual and remote access modes to enhance the students' learning. 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 Figure 4.1.

4.2 The Main Components of the Lab

The main components of the laboratory rigs, as shown in Figure 4.2, are: tank, rotameter, level sensor, control valve, voltage/pressure converter, pump and a USB Data Acquisition Device (DAQ). Tanks are normally where chemical engineering processes, such as reactions and crystallisation, take place. One of the basic control-loops to be found in the chemical industry is level control. Level control experimental rigs offer a good platform for demonstrating basic process control principles. With such rigs, students can easily observe the process change as opposed to temperature control or flow/pressure control demonstrating rigs. Level control processes have the advantage that they have a relatively quick dynamic compared to other control processes (such as temperature). This is particularly important because of the limited duration of laboratory sessions, which are often constrained to three hours or less.



Tank



Rotameter



Level Sensor



Control Valve



Digital Flow Sensor



V/P Converter



Pump



USB DAQ

Figure 4.2. The pilot scale level control rig main components.

In the Process Control Lab, there are five rigs with cylindrical tanks of different size and one rig with a spherical tank. The tanks' sizes and shapes promote different dynamic behaviour, which is introduced in the undergraduate and postgraduate courses at the department. The rotameter is used as a sensor for measuring the water inflow rate.

The level sensor used is pressure based and is located at the bottom of the tank. It measures the hydrostatic pressure and converts it into a voltage signal, which is used for estimating the water level in the tank. The most common final control element in the process industry is the control valve. The control valve manipulates the flow rate of a fluid, such as gas, steam, water or chemical compounds. For the process control rig, the control valve is responsible for regulating the water outflow. The control valves used for the pilot scale rigs are pneumatic with non-linear characteristics and hysteresis. The valves are fail-open types; hence they produce maximum flow at minimum signal. The control valve responds to the incoming signal from the PC through the data acquisition (DAQ) device. The incoming signal could be either manually generated by the operator or automatically generated through the implemented controller. The digital flow-meter is an electrical digital sensor used for measuring the outflow rate. The voltage to pressure (V/P) converter takes the control signal in the form of a voltage and converts it into a pressure that causes the control valve to open and close accordingly. A centrifugal pump is used to pump the water out of the tank with a constant rate that is independent of the level in the tank. The data acquisition is achieved via the national instruments USB kit, NI USB-6009. The unit contains eight analogue inputs, two analogue outputs and twelve digital input/output ports. The USB unit facilitates easy plug and play interfacing. The automatic controller itself is implemented by a LabVIEW-based software algorithm running on a PC which interacts with the process through the USB DAQ device. Further details of the software implementation are presented in Chapter 5 and Appendix 12.

4.3 The Main Concepts of the Lab

Feedback control systems loops are vital in chemical engineering. The absence of feedback control in many processes leads to economical inefficiency and could generate safety hazards. The lab aims to introduce the students to the main concepts and components of feedback control systems, according to the diagram shown in Figure 4.3. For instance, the actuator is the control valve, the process is the water tank, the measurement is done with the level sensor, the controller is

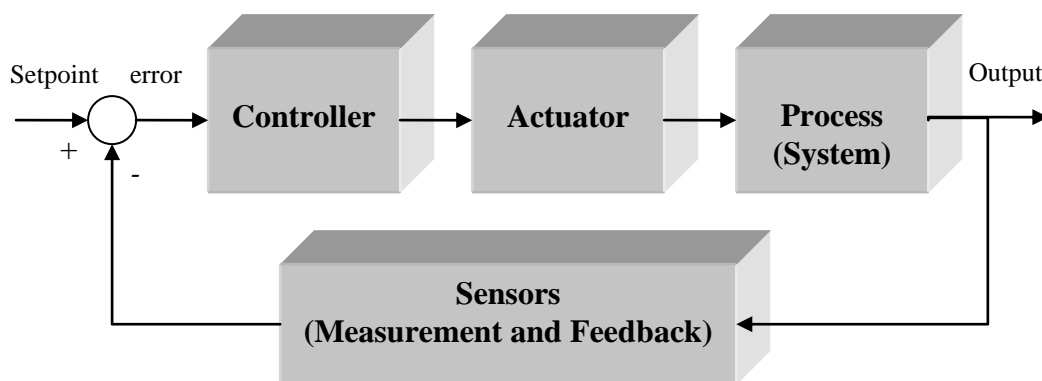


Figure 4.3. Main components of a control system feedback loop. Sensors measure the process output and feed it back for comparison with the desired input (setpoint). The controller acts based on the error value and provides a signal to the actuator to modify the process's dynamic behaviour towards the desired one.

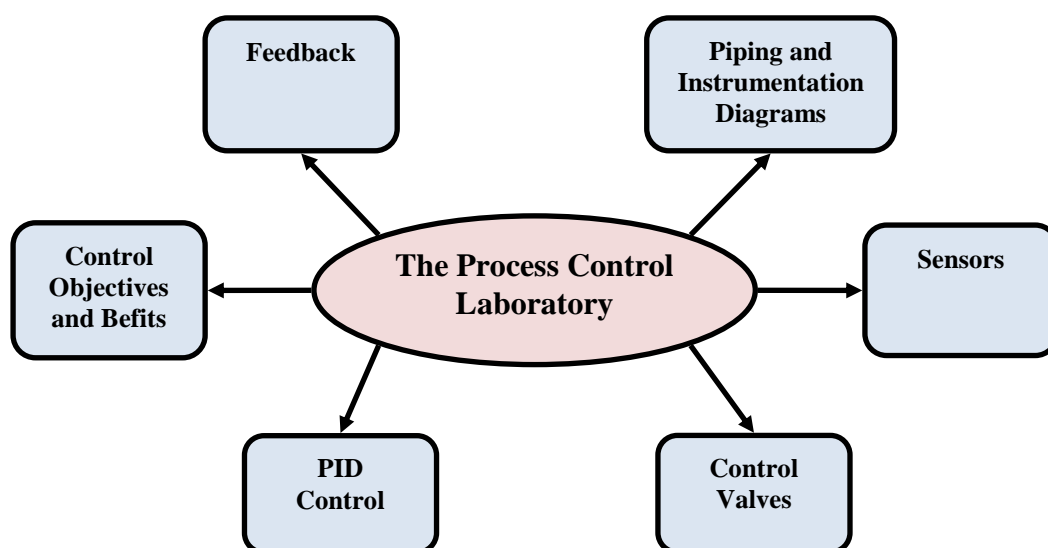


Figure 4.4. Conceptual model of the process control lab support of theoretical topics in the second year course Instrumentation, Control and Industrial Practice.

the embedded computer algorithm, the setpoint is the desired level, the output is the water level and the error is the difference between the actual water level measured through the sensor and the desired value set by the operator.

The second year course Instrumentation, Control and Industrial Practice which includes this lab as a compulsory component is to large extent structured around the feedback loop shown in Figure 4.3. The course aims mainly to develop an understanding of the principles of process control loops, their constituent components and how these interact to produce a control response both theoretically through classroom lectures and practically through two hands-on

laboratory sessions. The laboratory provides the students with authentic and tangible experience of some of the important theoretical parts of the course. The course is organised into independent topics. The laboratory supports the topics of control objectives and benefits, feedback, piping and instrumentation diagrams (P&ID), sensors, control valves, PID control and dynamic modelling, such as shown in Figure 4.4. Further details of the laboratory sessions and their objectives are provided later in this chapter.

4.4 The Process Controller

The controller is the tool that allows design freedom for the process engineer to alter the behaviour of the system through feedback control. PID control is the most widely used control algorithm in industry (Salzmann et al., 2000; Goodwin et al., 2001; Åström and Murray, 2008). PID controllers are common for a wide range of industrial processes. They are used, for instance, in controlling processes that include heating and cooling systems, fluid level regulation, flow and pressure control. The next subsection provides an overview of PID controller functionality.

4.4.1 The PID Controller Functionality

The PID controller calculates the error between the measured signal (Y) and the desired value, or setpoint (SP), and changes the manipulated value (e.g. valve position, C) so that the error is decreased. The amount of change in the manipulated value is a function of the error $E = SP - Y$, and is given by the following formula:

$$C(t) = C_s + f(E), \quad (4.1)$$

where $f(E)$ determines the controller type whether Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD) or PID, as follows:

$$C_p(t) = C_s + K_p E(t) \quad (4.2)$$

$$C_{PI}(t) = C_s + K_p(E(t) + \frac{1}{\tau_I} \int E(t)dt) \quad (4.3)$$

$$C_{PD}(t) = C_s + K_p(E(t) + \tau_D \frac{dE(t)}{dt}) \quad (4.4)$$

$$C_{PID}(t) = C_s + K_p(E(t) + \frac{1}{\tau_I} \int E(t)dt + \tau_D \frac{dE(t)}{dt}) \quad (4.5)$$

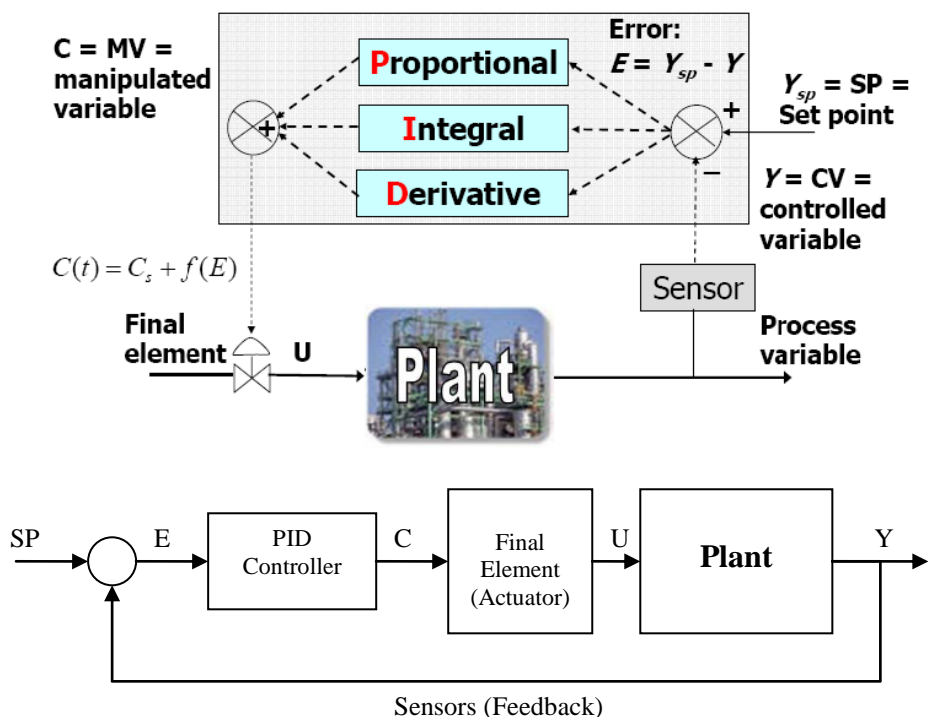


Figure 4.5. Intuitive diagram of process with PID controller together with a standard control systems block diagram representation.

where K_p is the proportional gain, τ_i is the integral time, τ_d is the derivative time, and C_p, C_{PI}, C_{PD} and C_{PID} refer to the control signal of P, PI, PD and PID controllers respectively. As seen from the previous equations, the members of the PID controller family include, in different combinations, three modes or actions that affect the controller behaviour: proportional (P), integral (I), and derivative (D) terms. The K_p, τ_i, τ_d are called the parameters of the controller. Figure 4.5 shows an intuitive diagram of a process with a PID controller together with a standard control system block diagram representation. The controller behaviour depends consequently on the values assigned to its parameters. Generally speaking, their effect on controller performance is as follows:

Proportional Action: It provides a contribution that depends proportionally on the error value. It can control any stable plant but is characterised with a non-zero steady-state error.

Integral Action: It gives a controller output that is proportional to the accumulated error (the integral term). Hence, it forces a zero steady-state error when a step change or a disturbance takes place, which is a very important aspect in controlling processes. However, it may lead to oscillatory or unstable behaviour and/or actuator saturation.

Derivative Action: It acts on the rate of change of the control error. Hence, it is a fast action of the controller as long as there is a change in the control error, e.g. the derivative of the error function is non-zero. Since it depends on the error trend, sometimes it is referred to as the predictive term. In the case of measurement noise, the error signal will be correlated with noise, yielding high frequency change in the controller signal when the derivative term exists. This is non-desirable in process engineering and this is why this action is often not used in controllers found in the process industries (Åström and Hägglund, 2005).

4.4.2 Building Computer-Based PID Control Algorithms

The PID controller presented in the previous sub section is a continuous function of time. Computers only process digital signals. Hence, continuous time systems connected to a computer for control should be communicating via analogue to digital (A/D) and digital to analogue (D/A) converters. D/A conversion can be achieved via the Zero-Order-Hold (ZOH) method (Åström and Wittenmark, 1997). In this approach, the D/A converter is structured in a way that holds the analogue signal constant until a new conversion is commanded. A schematic diagram of a computer-controlled system with ZOH is shown in Figure 4.6. The implementation of the digital PID control algorithm in LabVIEW is shown in Appendix 12.

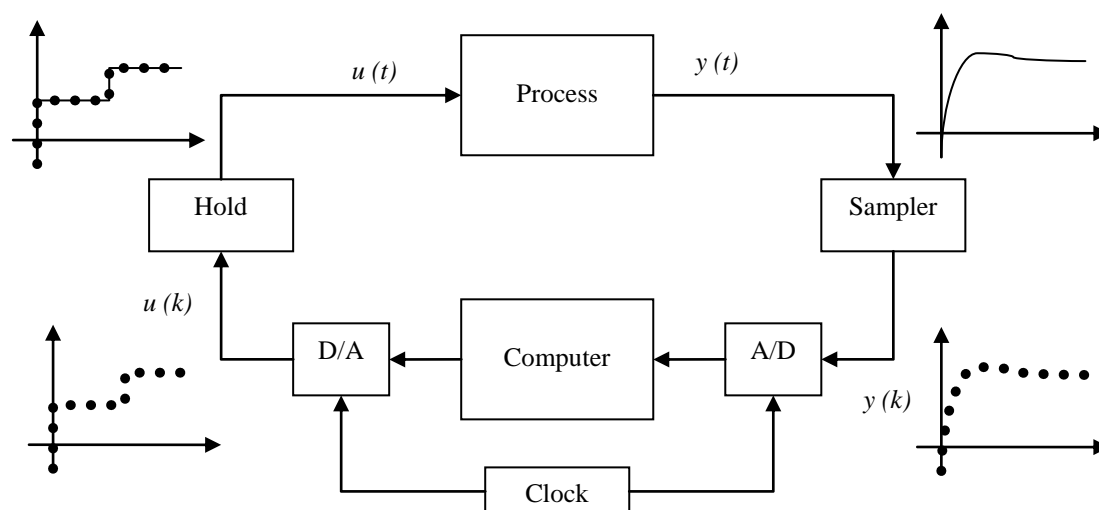


Figure 4.6. Schematic diagram of a computer-controlled system. The measured signals are conveyed to the computer through an analogue to digital (A/D) converter unit, the computer calculates the corresponding control signal in digital format. The control signal is sent back to the process through a digital to analogue (D/A) converter and a hold unit.

4.4.3 Tuning PID Controllers

PID controller tuning is the process of changing the controller parameters. Normally, this is done to achieve a better performance of the process. Most industrial controllers are used with default parameter values, which may not be the best for the process, hence it is important to tune PID controllers properly.

One of the most used model-based methods for PID controller tuning is the Ziegler-Nichols (Z-N) method introduced by Ziegler and Nichols (1942). When this method is used, it should be ensured that the open loop system is stable. Then the procedure is achieved following these steps:

- The plant is set under proportional control with very small gain that keeps it stable and not oscillating.
- The proportional gain is increased gradually until the process starts oscillating.
- The critical gain at which the process starts to oscillate (K_u) is recorded together with the oscillation period (T_u).

The PID controller parameters are then adjusted according to the values shown in Table 4.1.

Table 4.1. PID controller parameters obtained via the Ziegler-Nichols tuning method.

	K_p	τ_I	τ_D
P	$0.5 K_u$		
PI	$0.45 K_u$	$0.8 T_u$	
PID	$0.6 K_u$	$0.5 T_u$	$0.12 T_u$

Ziegler-Nichols based tuning of the PID controller can also be achieved in closed-loop systems. This is done by introducing a relay function to the system, such as that shown in Figure 4.7. This relay will generate oscillations in the system, hence the required information for tuning can be obtained, but without bringing the system to the limit of stability or generating oscillations with too high amplitudes, which may be impractical.

With such an arrangement, the system will normally oscillate with a critical period T_u . The critical gain is then computed by the following formula:

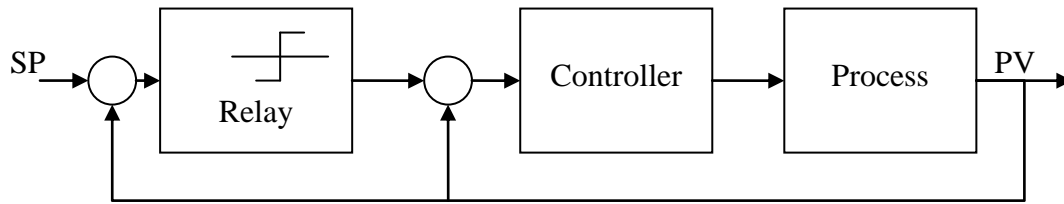


Figure 4.7. Block diagram of a process with relay feedback. The relay feedback produces oscillatory behaviour when it is introduced into the closed loop system. Data from the oscillations are used to calculate the Ziegler-Nichols tuning coefficients. (SP) is the setpoint, and (PV) is the process variable.

$K_u = 4d / (a\pi)$, where (a) is the amplitude of the process output and (d) is the relay amplitude. Then the PID parameters are calculated as shown in Table 4.1. The closed loop tuning with relay feedback is used generally in implementing automatic tuning software algorithms.

The Loughborough Process Control Lab contains a computer-based PID control algorithm implemented in LabVIEW and an auto-tuning algorithm based on the relay feedback method. Further explanations of the computer-based implementation of the PID tuning algorithm in LabVIEW can be found in Appendix 12.

4.5 The Multifunctional Armfield Process Control Rig

The process control lab has been supported by an additional modular control rig, the Armfield PCT40 multifunction process control teaching system, shown in Figure 4.8. The Armfield PCT40 system provides a cost-effective way of teaching a wide range of process control techniques. Some advanced process control features can also be demonstrated through additional optional modules such as a process vessel accessory PCT41 and a pH sensor accessory PCT42. Level, flow, pressure and temperature control loops can be demonstrated with the system.

The Armfield plant itself comprises a variable volume process tank, a hot water tank with electric heater and indirect heating/cooling coil, a hot water pump, two non-dedicated pumps, three on/off solenoid valves and a proportioning valve. The instrumentation includes temperature sensors, two differential water pressure sensors and a mechanical level sensor (float switch). The additional module PCT42 extends the rig functionality by adding a process vessel package that comes with a heating/cooling coil and a stirrer and with conductivity and pH probes. The inlets and outlets of the various pumps, valves and tanks are

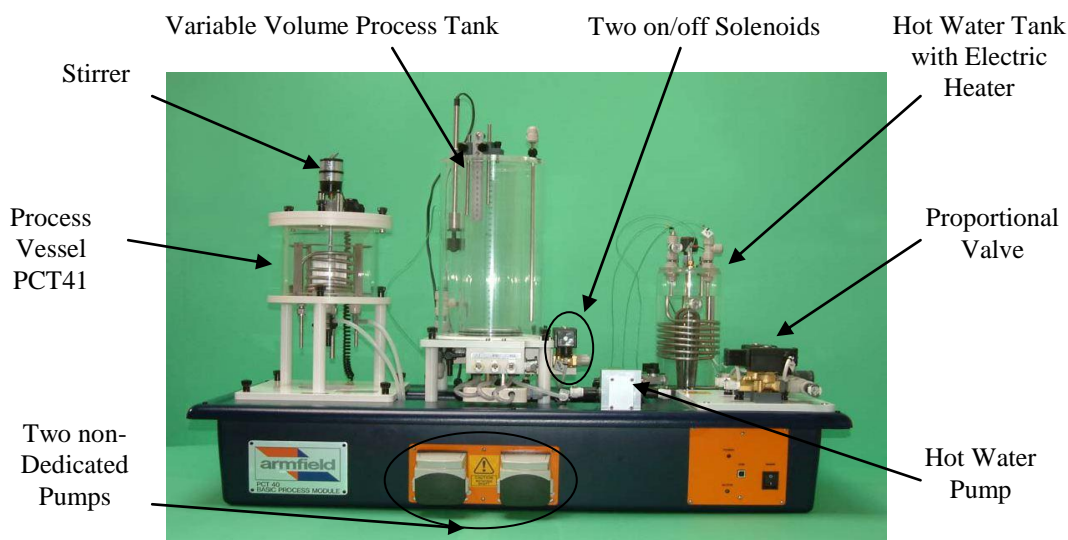


Figure 4.8. The Armfield PCT40 rig with PCT41 module. The unit can be used for demonstrating many process control exercises such as level control, heat transfer, pressure control etc.

brought to a connection manifold, which uses self-sealing quick-release fittings. The platform is multifunctional and can also be used for research experimentation. All the parameters (inputs/outputs), e.g. the pump speeds, the valve positions and the heater power can be controlled from a PC through a USB connection with the unit.

The system is supplied with an educational software package with a range of facilities and functions. A dynamic link library (DLL) driver for connectivity with LabVIEW, Matlab or C++ is also available. Hence, the didactic features can be extended beyond the associated software by designing specific Matlab or LabVIEW software systems.

The rig has been mainly used with the second year module as an additional rig to the six pilot scale rigs. The main utilised parts of the rig to compose a level control experiment are the variable process tank, of the non-dedicated pumps and the proportional valve; see Figure 4.8. This arrangement allows for a control level experiment that is similar to the other experiments undertaken with the pilot scale rigs in the process control laboratory.

The dedicated software of the rig does not include virtual or remote capabilities. Hence, it was necessary to develop LabVIEW-based software for the level control experiment with virtual and remote operation modes. Further details of the developed software are provided in Chapter 5.

4.6 The Undergraduate Laboratory Sessions

The hands-on laboratory of the second year module consists of two three-hour sessions, scheduled for two consecutive weeks. In the first week, the students are introduced to the typical elements of feedback loops such as sensors, actuators, controller and processes. The main objectives of the first session (instrumentation oriented) are: 1) calibration and hysteresis detection of the level sensor; and 2) calibration, hysteresis detection, installed characteristics and relative resistance of the control valve. During the second week, students are introduced to control engineering concepts. The aims of the experiments in the second week are: 1) to help students to appreciate the advantages of automatic control compared to manual operation; 2) to equip students with a qualitative and quantitative understanding of the differences between proportional (P), proportional-integral (PI) and proportional-integral-derivative (PID) controllers; and 3) to perform automatic tuning of different PID control structures. A detailed review of the laboratory sessions is outlined in the next two subsections.

4.6.1 The Instrumentation Section of the Process Control Lab

The instrumentation section of the lab takes place in the first week. In this lab session, the students become accustomed with the basic instrumentation principles and hardware that they may face in industry during their engineering career. The students become familiar with the components of the rig and how to operate initially during the start-up. In the first part they perform a simple test to understand the process dynamics and test the approximation that the water outflow rate can be considered an independent variable of the water level. In the next step they perform two main experimental procedures. The first is dedicated to water level sensor calibration, whereas the second is dedicated to control valve calibration as described in the laboratory manual. The calibration processes involve developing a proper procedure, taking measurements and estimating the characteristics and the hysteresis of the sensor and the valve.

4.6.2 The Control Section of the Process Control Lab

The second week of the laboratory sessions is concerned with learning feedback control principles. The objectives of the session are to gain familiarity with feedback control, to appreciate the importance of automatic control and controller tuning and to gain a qualitative appreciation of the effect of each term of the PID controller on control performance. The students start the session with a manual control exercise in which they are asked to control the water level at different set points. While conducting the manual control exercise, the students

realise that the level cannot be maintained without continuous manual manipulation of the valve and find the task difficult to accomplish, thus developing the motivation towards automatic control. They should also develop better understanding of the dynamic behaviour of the process and become aware of the importance of knowing the process dynamics for proper operation of the process.

After the manual control experiment, the students perform an extended set of exercises with automatic control using heuristic tuning and automatic control with auto-tuning, using the relay-tests that were explained earlier in this chapter. The aim of the automatic control and heuristic tuning exercises is to equip the students with a qualitative understanding of the effect of each PID controller parameter on the process dynamics. They test the impact of different values of each parameter and various control structures. In particular, the P, PI and PID combinations are explored thoroughly. By the end of these exercises, students should be able to determine which combination is the best and what the effects are of increasing or decreasing the value of each parameter. The automatic control with auto-tuning exercise aims to introduce the students to the concept of online automatic tuning of the PID controller parameters during the process operation in a closed-loop manner, using an already implemented automatic tuning algorithm. Such algorithms are commonly encountered in industrial control software (Åström and Murray, 2008). In the last exercise, the students test the impact of the controller sign change. The effect of the controller sign might seem trivial for novice engineers with very basic or no knowledge of PID control. However, the effect has a dramatic impact on the process since it changes the dynamic behaviour from stable to unstable. Once the students finish the last exercise, they shut down the rig, following a carefully designed shut-down-procedure.

4.6.3 Brief Discussion of the Two Laboratory Sessions

The laboratory experiments in the two sessions differ in nature. The first week has more emphasis on the instrumentation hardware; it aims to equip the students with hands-on experience of calibration procedures since calibration has a vital role in the chemical engineering industry. The second session has a more qualitative aim. It focuses on a qualitative understanding of the feedback loop and PID control. The PID principles are repeated several times through the second session, giving the students more time to comprehend the theory behind it. The first week's session generates a higher load on the students, firstly because it is the first time they encounter the system, and secondly because they

have only one trial in which to achieve the calibration procedures. Also, when the students come to the second's week session, they already have hands-on knowledge of operating the plant and understanding its mechanism as a result of the first week's session.

Generally speaking, the first week's experiment is designed more as a procedure-following exercise to help the students cope with the higher cognitive load required to familiarise themselves with the experiment setup, software and operation, whereas the second week's session is designed as an open-ended format, where the students have the chance to explore various aspects of PID control and tuning through repeated procedures. The full lab manual of the pilot-scale rigs can be found in Appendix 2. The Armfield rig was used in a consistent way with the six main rigs.

4.7 Conclusions

This chapter has introduced the physical rigs and the experimental procedures of the Loughborough Process Control Lab. There are six pilot scale rigs and one modular rig. The laboratory is a compulsory part of the curriculum of second year students at the Chemical Engineering Department of Loughborough University, and has been used in other courses. The laboratory was the test bed where the technical and pedagogical developments of this thesis in relation to laboratory education were achieved. A detailed description of the lab sessions of the undergraduate courses have been presented, as the core results of Chapter 6 were obtained with the students of these modules. The next chapter introduces a model of technical implementation of a hybrid (virtual, hands-on and remote) laboratory, with a case applied to the process control lab. Chapters 6 and 7 present pedagogical and statistical data analysis of the applications of the hybrid approach to teaching and learning in the Chemical Engineering Department.

Chapter 5.

THE TRI LAB MODEL OF THE PROCESS CONTROL LAB

Overview

This chapter introduces a new laboratory model, namely the TriLab. The model implements a triple access mode, where the hands-on experiment can be accessed remotely through the Internet and also can be conducted via a virtual (simulated) version within a common software environment. The TriLab approach is applied to the Loughborough Process Control Laboratory introduced in Chapter 4. The general architecture of implementing the TriLab with LabVIEW is provided. A development case of the TriLab with LabVIEW for the Armfield modular rig is detailed. The use of Joomla web content management system for the Loughborough online lab portal development is presented, with an introduction of the tool used for the collection of the statistics of the website. Finally, the TriLab as an enabler for the reusability of the experimental rigs is presented. This chapter introduces interested academics to a compact, one package recipe for constructing the TriLab with LabVIEW and for the World Wide Web outreach using Joomla for developing an online portal.

5.1 The TriLab Model; the Triple Access Mode Laboratory

Hands-on laboratories suffer from serious deficiencies, which were discussed in Chapter 3. Blending the hands-on lab experience with virtual and/or remote lab experience could result in better constructivist learning. This has been comprehensively discussed in Section 3.9. A hybrid triple mode model of laboratory education, so-called *TriLab*, is hence proposed in this chapter with extended details of its technical development.

The TriLab could be defined as *a hybrid laboratory model that utilises 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.

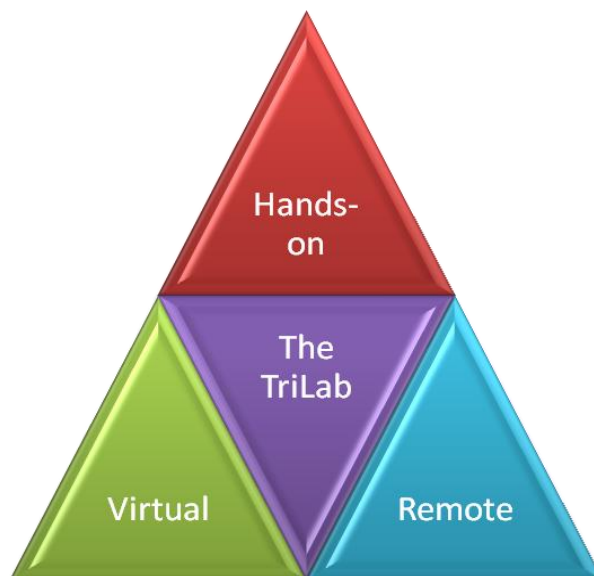


Figure 5.1. Conceptual model of the TriLab laboratory education model. The TriLab is a three access mode laboratory model where a user can conduct a lab experiment virtually and remotely in addition to the hands-on mode.

For instance, performing the experiment in the classroom can be correlated with the 'Concrete Experimentation' phase of Kolb's cycle, as it is a means of stimulating the students. The hands-on lab can be associated with the 'Active Experimentation' phase. The online lab, in addition to the virtual lab, is a way of facilitating the 'Reflective Observation' phase. The second cycle of learning can take place within a virtual or remote lab instead of a hands-on lab when it is not available or access is restricted. Further discussion of the pedagogically integrated use of the TriLab will be presented in Chapters 6 and 7. A conceptual model of the TriLab is shown in Figure 5.1.

5.2 Implementing the TriLab Model with LabVIEW

In implementing the TriLab, the designer would be advised to maintain the same interface and operation features as much as possible for the three modes. This could help to minimise the cognitive load (Sweller et al., 1998) for the student caused by dealing with a different software interface for each access mode. LabVIEW provides a generic development platform for achieving this purpose for a wide spectrum of engineering laboratories, as detailed in Chapter 3. This section introduces the implementation of the TriLab model with LabVIEW.

5.2.1 The LabVIEW Programming Environment

The LabVIEW development environment comprises three main parts, the *front panel*, the *block diagram* and the *icon/connector*. The front panel is the interactive GUI of a VI, named because it is similar to the front panel of a physical instrument. On the front panels, controls (user inputs variables) are placed as well as indicators (the LabVIEW programme outputs). The controls generally look similar to the physical buttons, switches and knobs that can be found on a conventional instrument. Controls supply the block diagram with the data needed for processing. The indicators receive the generated data by the LabVIEW programme and display them for the user.

The block diagram is the place where the actual VI's source code (developed with the graphical programming language: G) is contained. Hence, the block diagram is similar to the text lines found in conventional programming languages such as Java or C++. The components of the block diagram (the G-code) are lower level VIs, built-in functions, constants and programme execution control structures

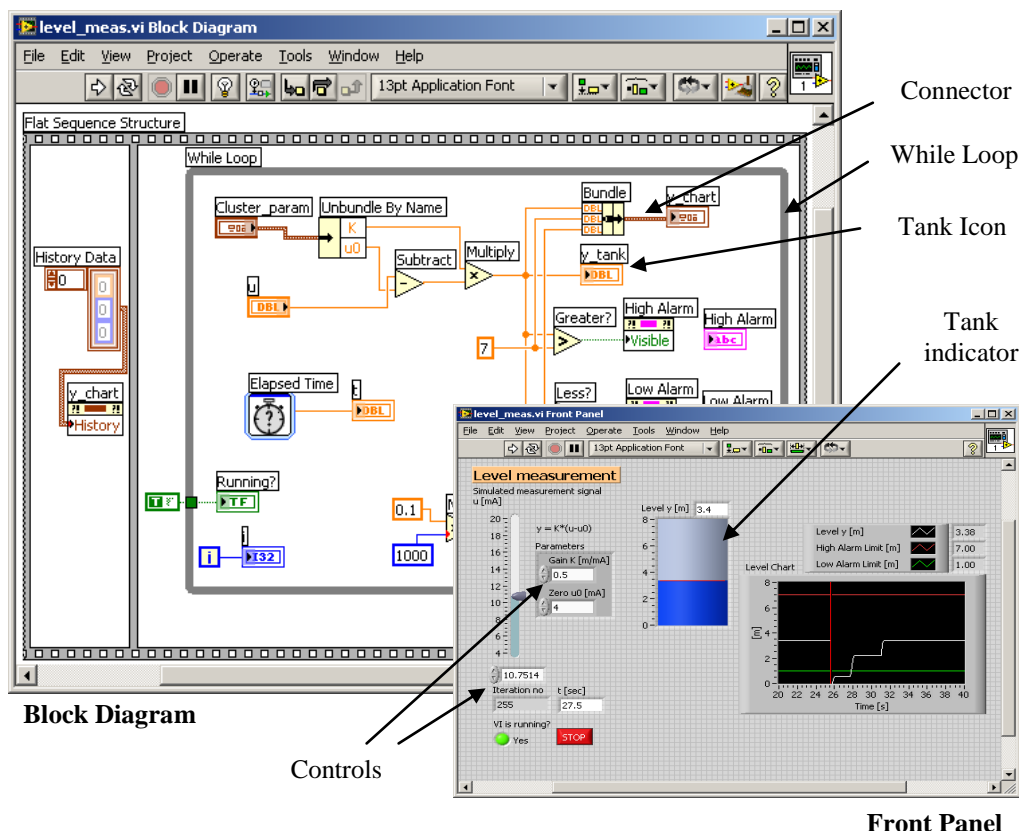


Figure 5.2. Tank simulation VI. The VI consists of a front panel (user interface) and a block diagram (programming panel). The block diagram shows graphical items (G-code) of the LabVIEW programming units.

such as 'For' and 'While' loops. An example of a LabVIEW VI of a tank simulation is shown in Figure 5.2. An executive summary of LabVIEW programming can be found in Appendix 12. The next subsection provides a summary of LabVIEW Internet publishing capabilities.

5.2.2 The LabVIEW Internet Connectivity Capabilities

LabVIEW offers many ways of establishing Internet connectivity. There are three main methods: 1) through the Internet connectivity toolkit; 2) through the built-in LabVIEW web server, web publishing and remote panels tools; and 3) through the LabVIEW web services feature which are included from LabVIEW 8.6 and onwards. The Internet connectivity tool was the oldest support of web connectivity provided by LabVIEW during the late 1990s and is still supported in the newer versions. The built-in web server, web publishing and remote panels features were introduced later to make Internet publishing more feasible. With the LabVIEW built in web server, the user can publish a VI through the LabVIEW web publishing tool in one of the following three modes:

- **Snapshot:** This is a static image of the VI's front panel.
- **Monitor:** This is an image of a VI's front panel that is refreshed every N seconds. The user can configure the N parameter.
- **Embedded:** In this option, a controllable version of the VI front panel is published as an embedded plug-in at the client's browser. Hence, the VI is displayed in real time at the client's side and the client has control over it.

The web services feature was developed to give the LabVIEW programmer greater flexibility in building the Internet application. It helps to establish communication between LabVIEW VIs and other web technologies such as Java or Flash, e.g. for developing Java-based applications that can communicate with LabVIEW VIs running on a LabVIEW web server. The remote labs developed in this work have been implemented through the LabVIEW built-in web server and web publishing tools. The next subsection provides details of implementing the TriLab model with LabVIEW.

5.2.3 Implementing the Virtual, Hands-on and Remote Lab Components of the TriLab with LabVIEW

LabVIEW was originally developed by National Instruments (NI) to offer an integrated platform for hardware interfacing, data acquisition (DAQ) and analysis with computers (Travis and King, 2007). National Instruments offers a wide spectrum of data acquisition hardware ranging from a simple USB DAQ to

high quality industrial DAQ systems. For many educational laboratory rigs, the USB DAQ can be sufficient for the required input/output communications, providing a cost-effective solution.

LabVIEW software for a hands-on lab rig consists of two main parts. The first part is the LabVIEW code for data coordination, manipulation and visualisation (DCMV), while the second part is the LabVIEW code for interfacing with the rig through the DAQ. The DCMV code communicates with the rig through the DAQ code to coordinate the input/output data flow, manipulate and analyse it, direct it to the appropriate visualizing components on the front panel and to process the user input. For building a virtual lab in LabVIEW, a mathematical model of the lab process with equivalent input/output ports replaces the physical rig and the DAQ code. An efficient way of implementing equation intensive mathematical models is to use one of the LabVIEW mathematical script tools such as the 'MathScript Node', the 'Matlab Script', or the 'Formula Node'. Another alternative is to programme the equations with G-codes if the model is not too complex.

Once the core LabVIEW software of the hands-on/virtual lab has been implemented, remote connection to the Graphical User Interface (GUI) of the software can be done via the web publishing options mentioned earlier. The connection process can be achieved as follows: the web publishing tools of LabVIEW implement an HTML code that embeds the VI of the laboratory software. This HTML code is stored in the LabVIEW web server root directory. The root directory can be specified in the LabVIEW web server configuration window or in the initialisation file of the executable application. To access the VI remotely, the LabVIEW web server is activated. Then the VI can be accessed via the server name. The whole software application can be compiled together with the LabVIEW web server and the LabVIEW runtime engine in the installation kit. The application can be configured through an initialisation file to be installed in the root directory of the executable file. In this way, a stand-alone application that includes the hands-on lab interface, the virtual lab and the remote access option of the rig can be developed and distributed, making the final application available to users who do not have the LabVIEW development environment.

When a client requests a webpage that includes the HTML code of the embedded VI of the lab software, the VI will be uploaded to the client's PC. Hence, the user will be able to communicate with the lab rig remotely through the LabVIEW web server. Since most clients may not have the LabVIEW development platform installed on their PCs, the remote VI will not operate until the LabVIEW runtime engine is installed. The latter is available to download free from the NI website.

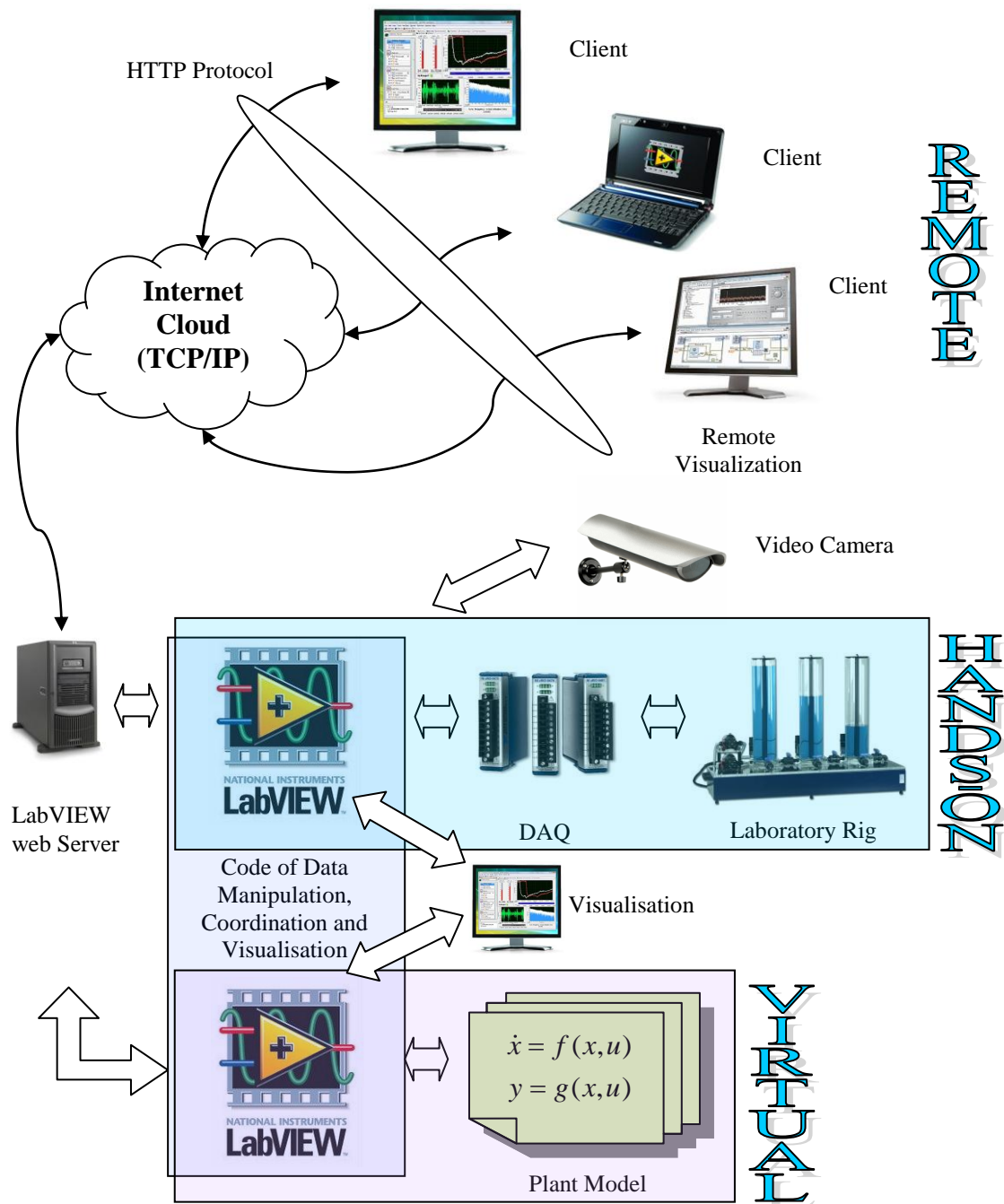


Figure 5.3. The architecture of the TriLab model with LabVIEW. The LabVIEW software of a hands-on lab can be expanded to virtual lab software by replacing the rig DAQ ports with a mathematical model of the process. The whole software can then be embedded in an HTML code and be available for online operation through the LabVIEW web server.

This process is similar to many Internet embedded applications such as Flash files, or Java applets that require the installation of special software on the client's PC to enable the functionality of the embedded application. The LabVIEW web server passes the client input to the local VI that resides on the server (which is interfaced with the rig) and feeds back the data to be processed and visualised at the client's remote panel.

It has been stressed that remote labs should be accompanied by video transmission of the experiment (Salzmann et al., 2000; Srinivasagupta and Babu, 2003; Kwon et al., 2007). This can be achieved through a video camera connected to the server. LabVIEW can be interfaced with this camera and the video transmission can be embedded in the LabVIEW software. The other alternative is to use an Internet Protocol (IP) video camera, which will have an embedded web server and can transmit the video images independently through the Internet without the need to connect to a PC with a web server. Figure 5.3 shows the TriLab model architecture with LabVIEW.

Having discussed the general architecture of the TriLab model with LabVIEW, the next section shows how this has been utilised to implement the TriLab for the process control lab. Since the lab involves two different types of rig - modular and pilot scale - an extended description is provided for one type, and finally a section outlining the minor differences for the other type is presented.

5.3 The TriLab Software for the Level Control Experiment of the Armfield Rig

The Armfield rig accompanied by its educational software offers many process control experiments. However, the software includes neither a virtual lab nor a remote lab for any of the possible experiments with the Armfield rig. One of the objectives of this project is to deploy the Armfield modular rig in the process control lab as the seventh rig to accommodate the increasing number of undergraduate students and to build a TriLab system of the control level experiment of the rig with LabVIEW. This also aims to offer a compact remote rig that can be easily operated online without the need for human intervention onsite.

5.3.1 The LabVIEW Code of the DAQ Interface with the Rig

The rig is connected to the PC through the USB port; this arrangement eliminates the need for a separate DAQ unit. However, it has introduced the task of building a dedicated LabVIEW driver for communicating with the rig through the USB port. This communication has been built via a DLL file, which can be read in LabVIEW through the 'Call library' function. There are analogue and digital sensors in the rig as well as analogue and digital actuators, which all need an interfacing code. A generic LabVIEW driver for the Armfield rig has been developed, which provides access to all digital and analogue inputs and outputs. The G-code for writing to the process analogue and digital controls variables is

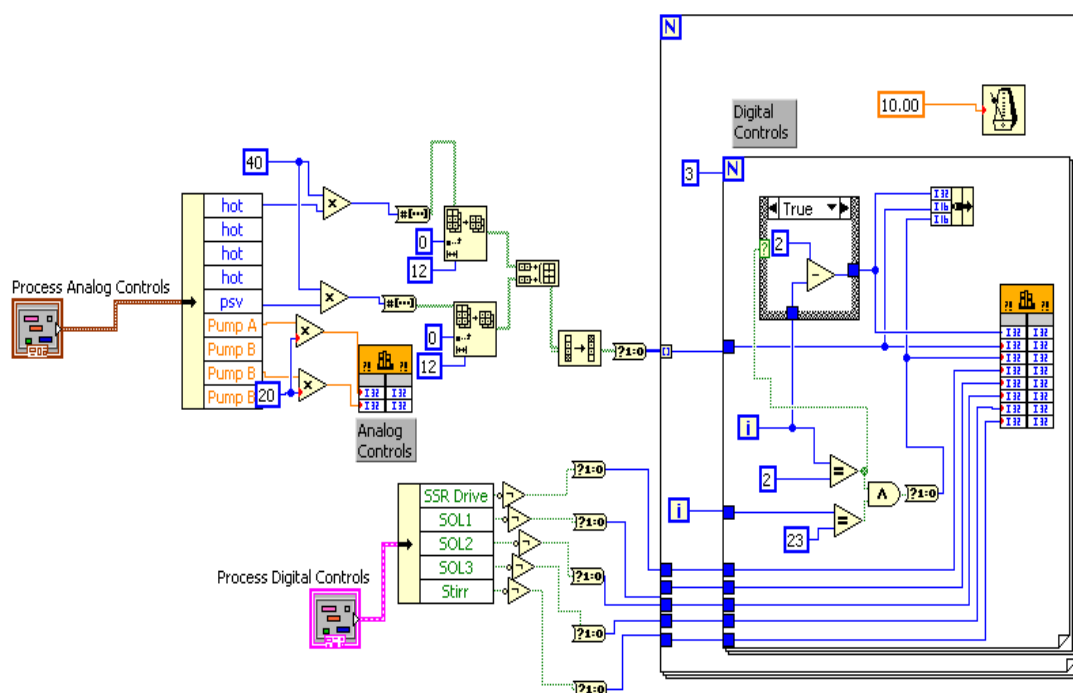


Figure 5.4. Digital and analogue Armfield controls G-code driver.

shown in Figure 5.4. Further information about the LabVIEW G-code of the driver and other components of the level control experiment of the Armfield rig are detailed in Appendix 12.

5.3.2 The Software Architecture

The Armfield level control experiment has been implemented following the LabVIEW-based TriLab architecture explained in the previous section. The software code comprises of the following main components:

- The controller, which includes the PID control and auto-tuning algorithms.
- The data manipulation and coordination code.
- The visualisation and the user input interface.
- The experiment, which can be conducted either through a simulation of a mathematical model of the process or through communicating with the physical rig via the DAQ interfacing code.

The level control can be achieved either by manipulating the inflow rate (with the proportional valve) or by manipulating the outflow rate (with one of the non-dedicated peristaltic pumps) depending on user preference. The control action

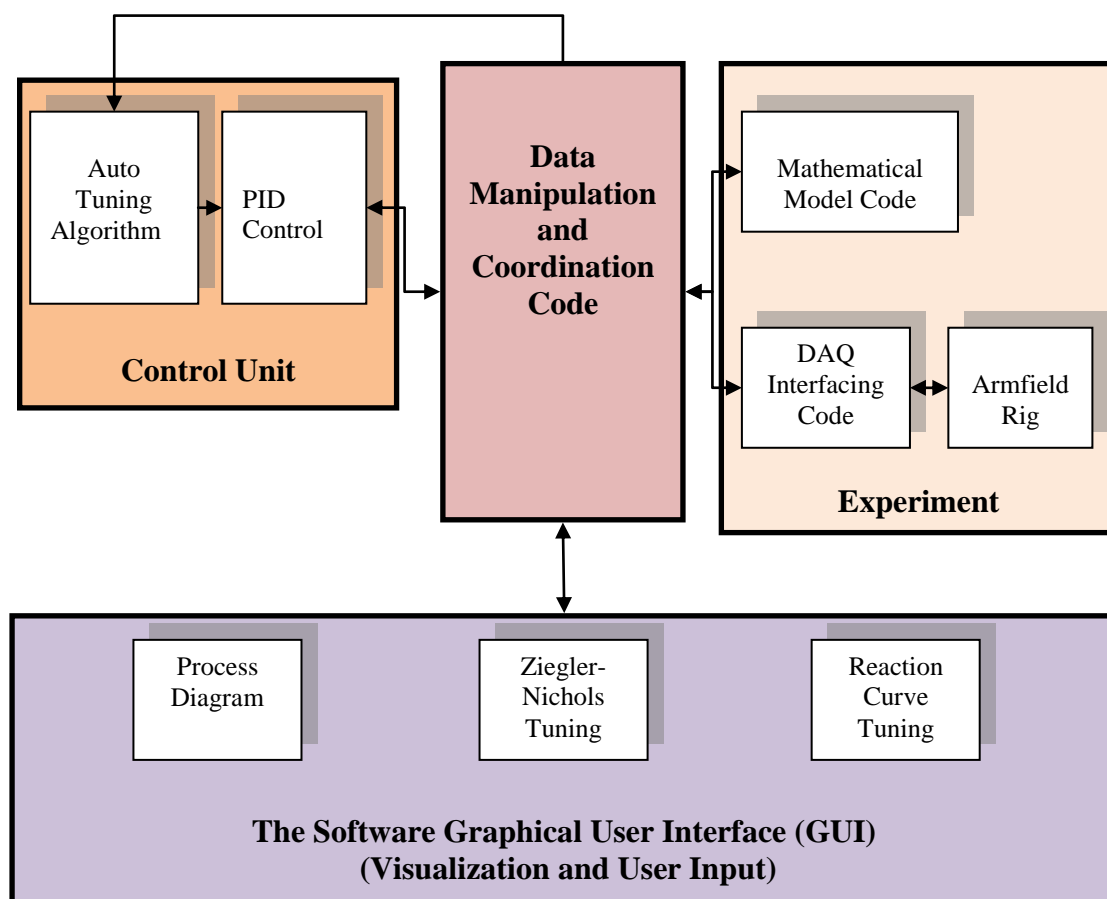


Figure 5.5. The main components of the Armfield software. The control unit contains algorithms of PID control and PID Auto-tuning. The experiment is either virtual or real. The GUI provides three panels, one for the process and the other two for the Ziegler-Nichols and the reaction curve tuning exercises.

can be automatic or manual. When automatic control is chosen, the user can tune the PID controller parameters manually or through an auto-tuning algorithm. The PID controller and the auto-tuning algorithms are both implemented in LabVIEW.

The data manipulation and coordination code is the main body of the software. It is responsible for manipulating the data received from the user and from the other software components. Also, it is responsible for saving and processing the data and handling the video transmission. The visualisation and user interface component of the software (the front panel) is responsible for representing the data to the software users and receiving their input. The main panels in the software interface are: Process diagram, Ziegler-Nichols tuning and reaction curve tuning. Figure 5.5 shows the general architecture for the TriLab software of the level control experiment of the Armfield rig.

5.3.3 The Software Graphical User Interface

The software graphical user interface comprises three panels: the process diagram, Ziegler-Nichols tuning and reaction curve tuning. The process diagram panel presents the process schematic with interactive virtual instruments. It provides the user with the ability to choose between manual and automatic control, to choose between inflow and outflow control, to set the required setpoint and to set the inflow and the outflow rates of the water. In this window, the user can choose to run the level control process under simulation or real DAQ mode. When connecting to the software remotely, the user can specify the data file name. The file will be updated and stored automatically in a root directory of the LabVIEW web server. The user receives the link to download the data file by pressing the download button. The live webcam window enables the remote user to view a live video streaming of the process while in operation, which leads to higher perception of the experiment's authenticity (Salzmann et al., 2000; Srinivasagupta and Babu, 2003; Kwon et al., 2007). Figure 5.6 shows the process diagram panel of the software. The user can manipulate the PID controller parameters $K_c = K_p, T_i = \tau_i, T_d = \tau_d$ from the process diagram panel. The user can also choose the 'Autotune' option, which runs an automatic tuning wizard. The automatic tuning wizard provides the user with the option to tune the controller parameters in three modes - slow, normal and fast - which can be applied for P, PI or PID structures, hence giving nine different options of controller tuning. The auto-tuning process estimates the process noise, then applies a relay signal for a period to estimate the process dynamics and finally provides the required controller parameters after executing an internal calculation algorithm. The data is visualised in numeric values and through plots in the main chart. Also, the change in the water level is simulated via a tank indicator. This structure accommodates Visual and Kinaesthetic learners (VARK, 2009). On the other two panels, users can practise Ziegler-Nichols tuning and reaction curve tuning. Figure 5.7 shows the panel for the Ziegler-Nichols tuning exercise. For instance, a user can follow the procedure of Ziegler-Nichols tuning explained earlier in Section 4.4.3 and bring the process into oscillation. The user can provide the needed parameters K_u and T_u in the specified controls of the panel, and then the software calculates the corresponding parameters of the PID controller. Simulated and real experimentation can be conducted remotely if the software interface is published online. The general flow chart of the software algorithm is shown in Figure 5.8.

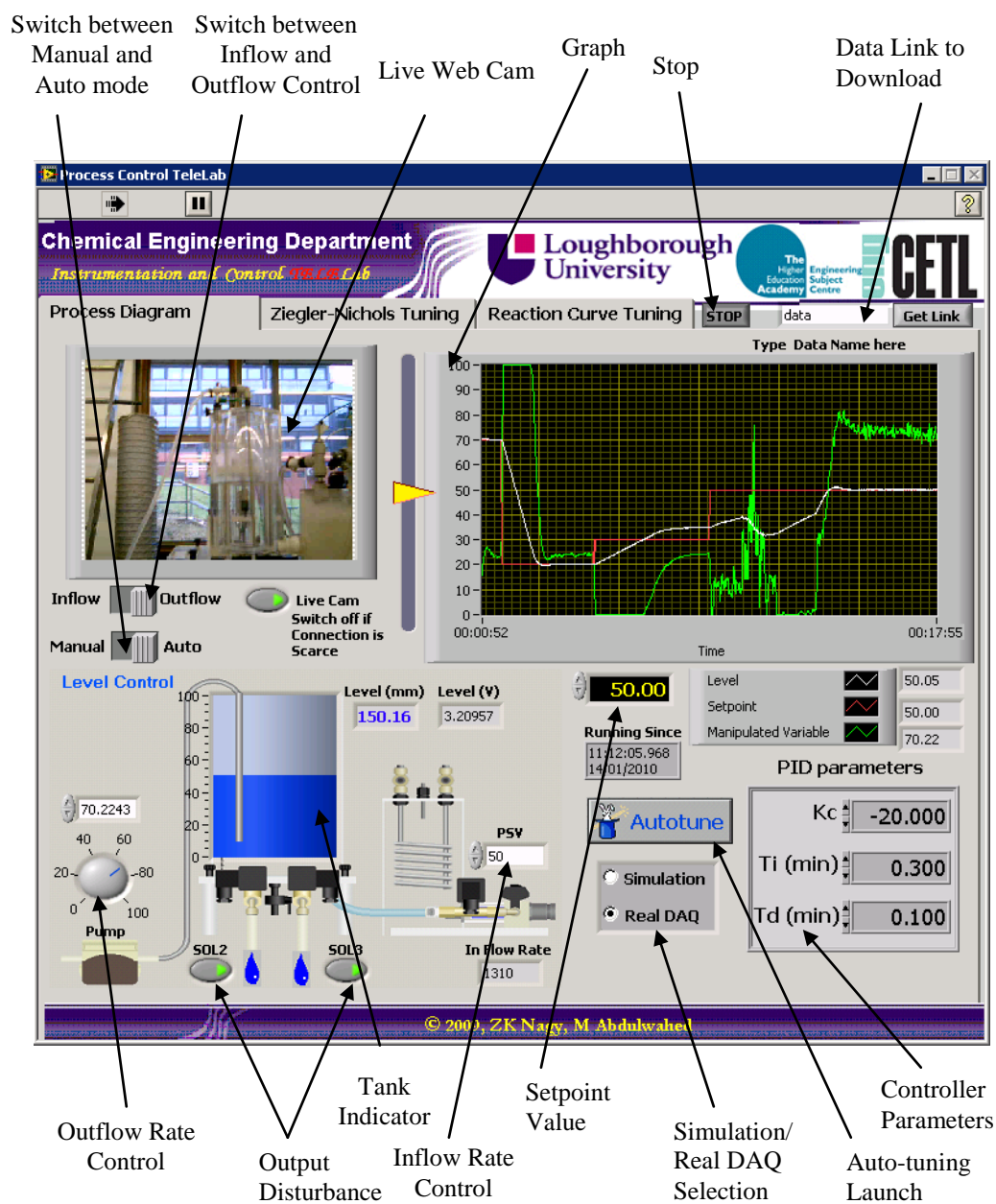


Figure 5.6. The Armfield TriLab process diagram panel.

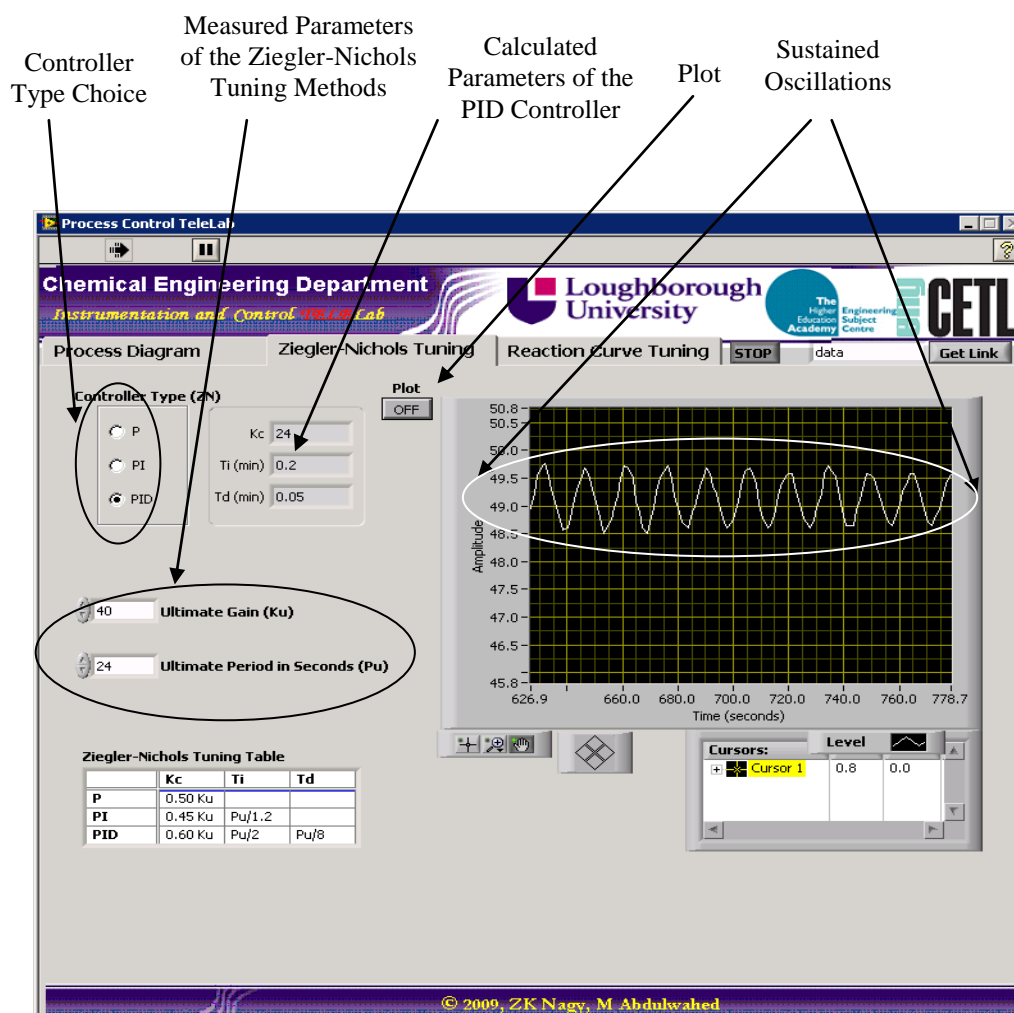


Figure 5.7. The Ziegler-Nichols tuning panel of the Armfield TriLab software.

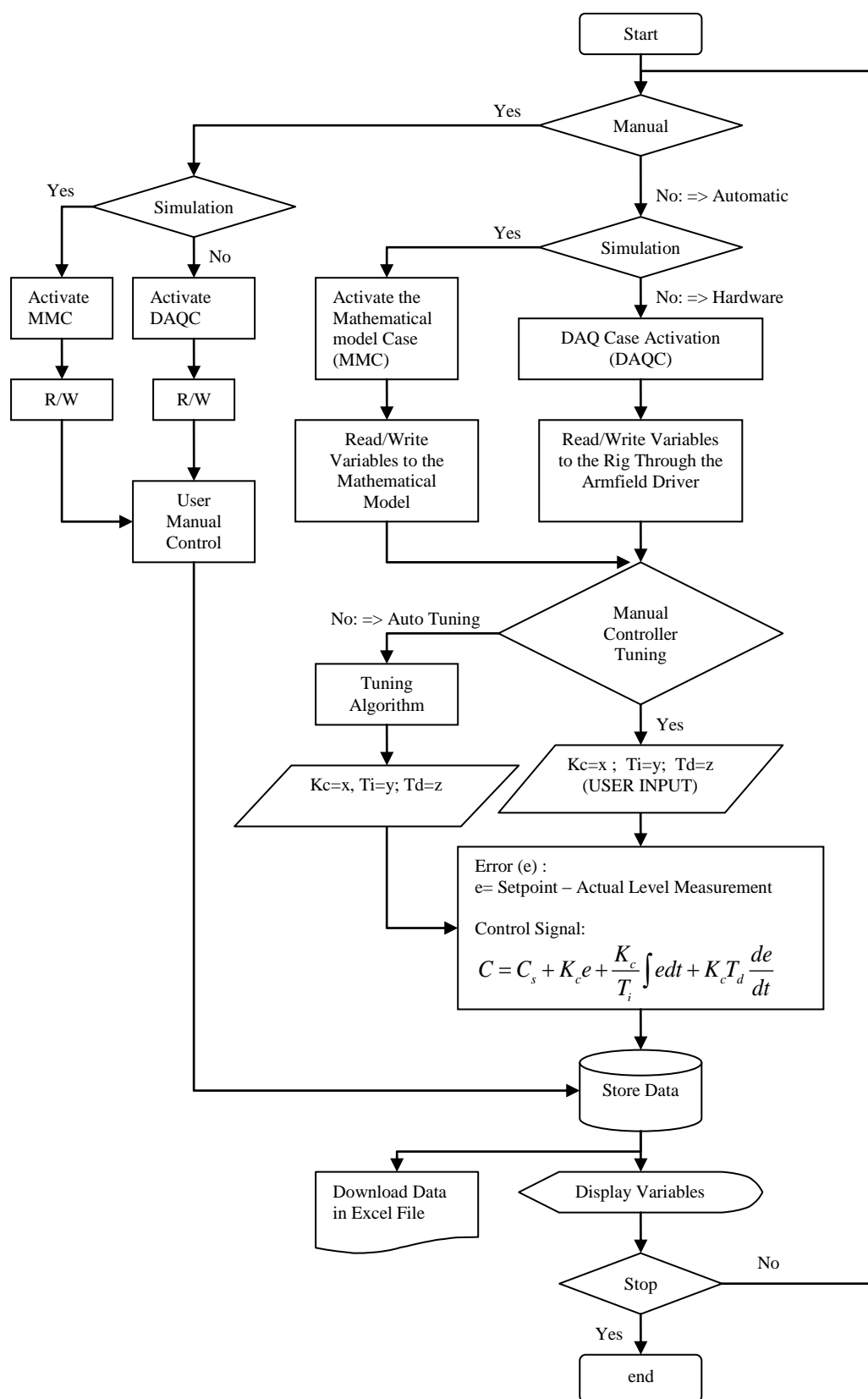


Figure 5.8. The flowchart of the control level software algorithm.

5.4 The TriLab LabVIEW-Based Software of the Six Rigs

The same TriLab software concept that is applied to the Armfield rig is also applied to enable a triple mode access for the other six pilot scale rigs. There are a few minor differences:

- The level control can be achieved only through the outflow rate manipulation.
- The DAQ system is different. For data acquisition in those rigs, a national instrument USB DAQ kit has been used, as shown in Figure 4.3.
- There are three pages in the software interface (Process Diagram, Controller, and Configuration).

Apart from these differences, the software is rather similar and the general algorithm shown in Figure 5.8 applies. The process diagram page of the software is shown in Figure 5.9.

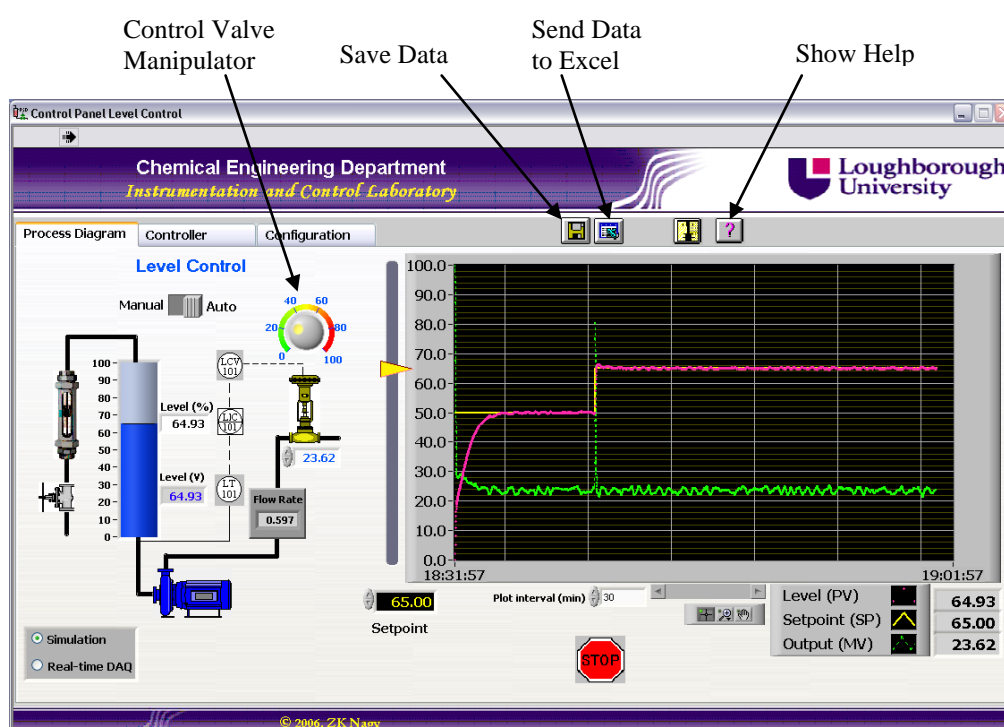


Figure 5.9. The LabVIEW interface of the pilot scale rig.

The software stores the needed data through a storing code. When the local user presses the 'send to excel' button, a Dynamic Data Exchange (DDE) procedure is activated, allowing the data to be shared between LabVIEW and the Excel application of Microsoft Office. This arrangement will open an Excel file and all

the stored data from the beginning of the application run will be saved in the opened file. The DDE is a function that allows data sharing between Windows applications. The user also has the capability to start storing data in an Excel file at a specific time and stop the process by pressing the 'save data' button. These features are deactivated when the software is used remotely, and instead the 'download' button is active, as is the case for the Armfield rig.

The six rigs have been made available online together with the Armfield rig. These are promoted through an online portal, namely the *iLough-Lab* portal. In the next section, a description of the implementation and content of the Loughborough remote lab portal is presented.

5.5 The Implementation of the Online Laboratory Portal of Loughborough University with Joomla

This section details the process of implementing the first online laboratory portal of Loughborough University by using the Joomla web content management system. The portal is one of the few remote laboratory hubs available in the UK.

5.5.1 Choosing the Domain Name, the Hosting Package, and the Development Platform of the Online Portal

The chosen name of the portal is www.ilough-lab.com. The name was derived as follows: 'i' from Internet, 'lough' from Loughborough, and 'lab' from laboratory, and has the auditory connection 'I Love Lab'. The aim was to provide an address which is characteristic and easy to remember. The domain name was reserved with a hosting package through a web hosting service provider (Hostmonster, 2009). As was detailed in Chapter 3, Joomla is one of the best solutions for building dynamic portals; hence, it was chosen to implement the iLough-Lab.

5.5.2 Joomla Web Content Management System Architecture

As other open source WCMs, Joomla is free and targeted at non-technical personnel to enable them to flexibly manage complex websites. It also provides additional tools to help add more functionality to the aimed website, such as guestbook, forum and events and calendar. The Joomla system comes with a user-friendly and easy to navigate administrator control panel for managing the content. In this section, further details of Joomla features and architecture are provided.

The main architecture of Joomla comprises the following units: content, content items, category, section, module, plug-in, component and a template which

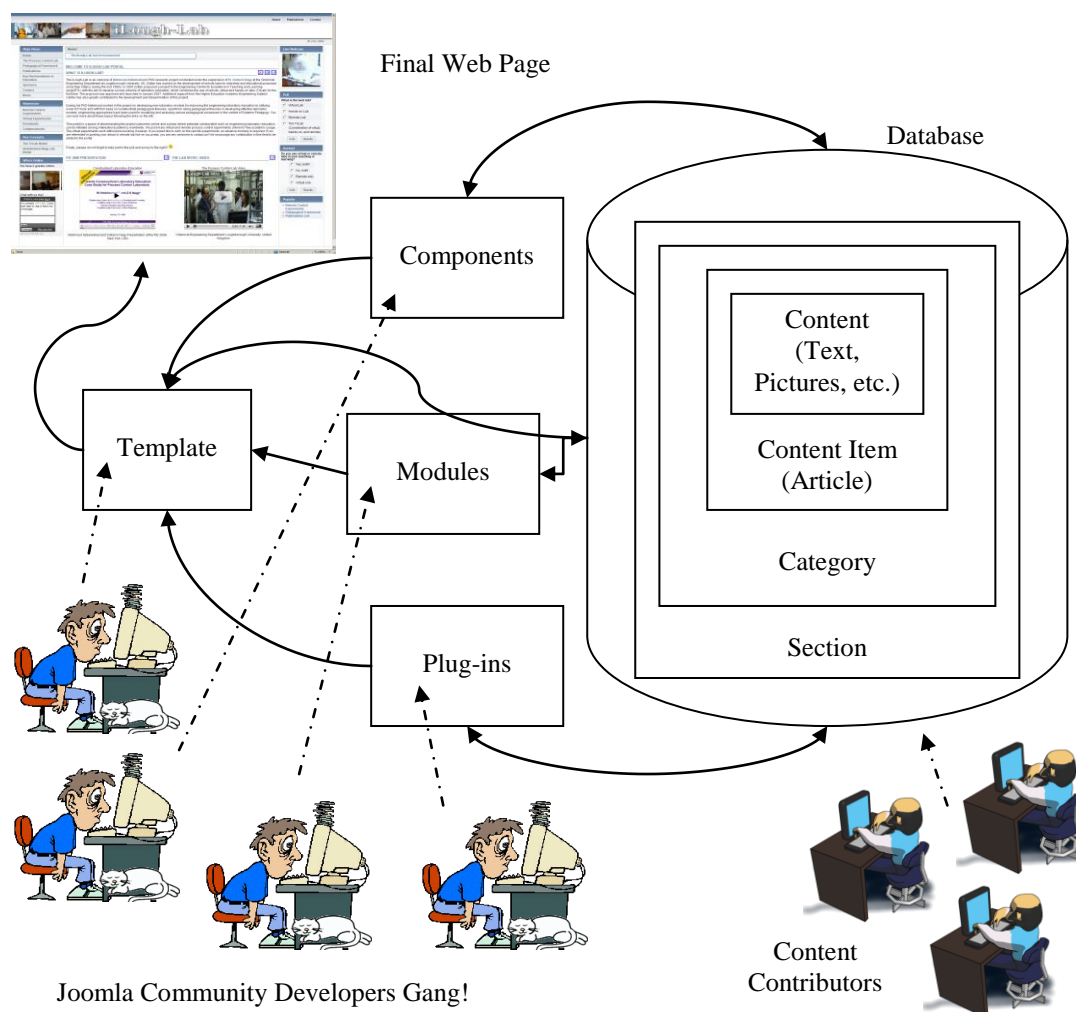


Figure 5.10. General architecture of the Joomla! CMS.

envelopes all the previous units. Content is basically the text, pictures and media of the website. The content is normally organised in content items called articles. The articles are the lowest layer of a hierarchy of three levels. A category is the middle level of the hierarchy and holds one or more content items. The top layer is a section, which holds one or more categories. In brief, Joomla! uses sections, categories and articles (or content items) as a mechanism for organising the content, similar to directory folders and files in a standard file system. The data that makes up the content is stored in a MySQL database. Joomla's administrator application is basically a GUI for that database.

Modules are Joomla's windows of the website's front end. They are placed around the website edges, surrounding the main content in the centre. The website menus, for instance, are shown in modules. Modules, in principle, are the main user interface with a Joomla-based website. Plug-ins are small programs to be run before any article is shown on the website for embedding extended

functionalities in the articles. Plug-ins are normally provided with configuration parameters. Components are Joomla web applications that can be installed as add-ons to the Joomla features that come with the basic version. Finally, the template is the vessel for displaying a Joomla website. The template consists of an index.php file that defines the layout of the site's pages, and a cascading style sheet (CSS) file to define the formatting to use. The template determines the module positions on the screen, fonts and colours etc. The main power of Joomla is in its extensibility. Since Joomla is an open source system, interested developers worldwide can contribute their extensions to the system. These third party extensions can be components, modules, plug-ins or templates, and account for 3175 extensions developed by the Joomla community as of August 2009 (Joomla, 2009). Figure 5.10 shows a diagram of the Joomla architecture. Some information of the technical requirements of Joomla can be found in Appendix 13, and further comprehensive details of the system can be found in the book by LeBlanc (2007). The next section shows how Joomla has been used to implement the iLough-Lab portal.

5.5.3 The Joomla-Based iLough-Lab Portal

The portal aims to envelope developed remote labs. It also aims to contain additional information about the experiments, the research project, related literature and polls. Joomla was adopted as a solution for building the portal. Following the Joomla hierarchical structure, five main sections were created. Each section contains a number of categories to organise the website data, such as that shown in Table 5.1.

Table 5.1. The iLough-Lab portal content hierarchy.

Sections	Categories	Items
Main	Main Information, Front Page	Static Articles
Resources	Virtual Labs, Remote Labs, Other	Static Articles, Referring Articles
Key Findings	Pedagogical, Technical	Static Articles
Media	Webcams, Presentations, Video	Mesh-up Articles
News	General, Lab News	Static Articles, Referring Articles

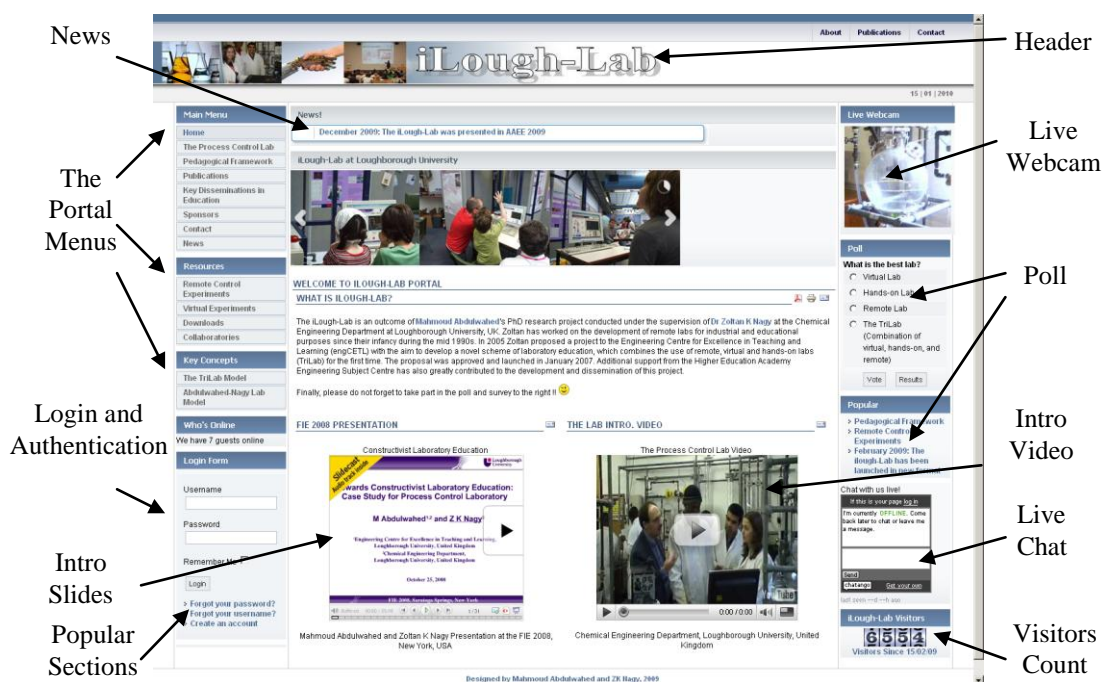


Figure 5.11. The iLough-Lab portal as developed with Joomla.

The main section and its categories include articles of a general information nature. The resources section and its categories contain the referring articles to the virtual and remote labs of Loughborough University and other articles as resources, e.g. downloads. The key findings section is meant to group pedagogical and technical models of the project. The media is meant to group all media types such as the live webcams, video demonstrations and PowerPoint presentations. The news section groups project-related news in two categories: a general one and a lab-related one. The iLough-Lab website template has been adapted from one of Joomla! free templates. A new header has been designed, and some PHP coding was performed to adapt the template to the needs of the website.

The main web page of the portal (see Figure 5.11) contains general information about the project, an introductory video and the Frontiers in Education 2008 conference presentation related to the project (Abdulwahed and Nagy, 2008). For embedding the latter two, mash-up technology has been used. The video was uploaded onto YouTube servers (YouTube, 2009) and then an embedded HTML code was integrated into a Joomla! article. Following that, the article has been published on the portal front page. The same procedure has been applied to the FIE 2008 presentation. The PowerPoint file was uploaded to SlideShare servers

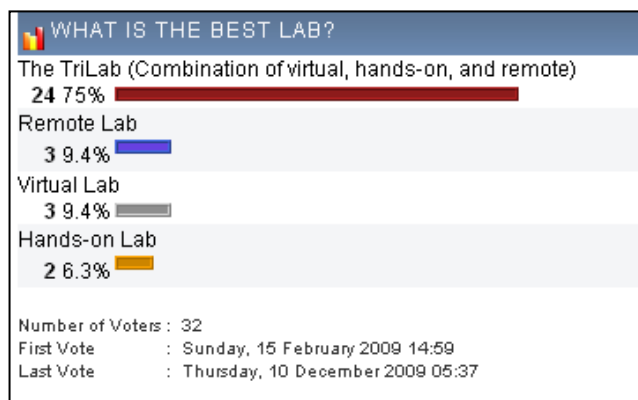


Figure 5.12. The iLough-Lab Poll ‘Which is the best Lab?’ Users voted highly for the TriLab concept.

(SlideShare, 2009), which provides special functionality for navigating PowerPoint presentations.

To the left (see Figure 5.11) there are the following items: Main menu, Resources menu, Key Concepts menu, Who’s Online menu and a Login menu. The main menu contains links referring to general information such as the process control lab, the pedagogical framework, the publications, sponsors and news. The key concepts menu refers to the two main laboratory models developed alongside this work, the TriLab model that was described earlier in this chapter and the Abdulwahed-Nagy constructivist laboratory model (Abdulwahed and Nagy, 2009a), which will be introduced in Chapter 6. The Who’s online menu shows the number of current visitors to the website. The resources menu contains links leading to the available remote and virtual experiments, downloads, and links to other remote labs worldwide.

To the right of the portal there are the following items: Live Webcam menu, Poll menu, Popular menu, Chat menu and Online Visitors counter. The Live Webcam menu shows a live video streaming of one of the lab rigs. The Poll menu aims to collect the clients’ opinion of what is the best laboratory style (Virtual, Hands-on, Remote or the TriLab). The poll was published on 15th February 2009. The counts show that the majority of users (75%) prefer the TriLab option to a single mode lab. The least preference was given to the hands-on lab (6.3%), probably because of the limitations associated with accessing hands-on labs in general. The remote lab and the virtual lab options are equivalent, with 9.4% for each. The results clearly show that laboratory users prefer multiple accesses to an experimental rig. Figure 5.12 shows the poll results with the last vote obtained

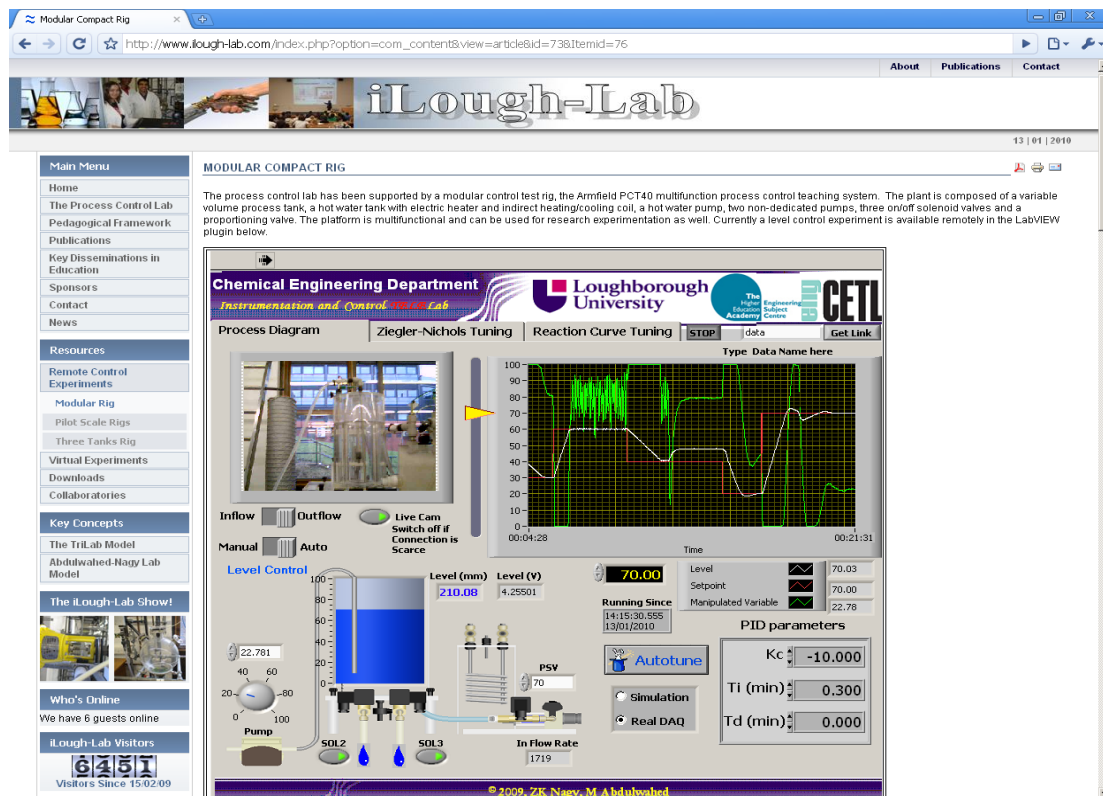


Figure 5.13. The Armfield modular rig operating remotely through an embedded VI inside the Joomla-based portal.

on 10th December 2009. The chat menu provides a live chat interface with the site visitors.

The LabVIEW remote lab plug-in has been integrated into a Joomla article using a third-party extension which allows an HTML source code to be embedded into Joomla's articles. Figure 5.13 shows the LabVIEW remote panel of the Armfield software embedded into Joomla and operating online.

Using Joomla has led to the design and implementation of a dynamic and user-friendly portal with rich features. The next section introduces a tool for traffic statistics collection over online portals such as the iLough-Lab.

5.5.4 The iLough-Lab Site Statistics

It is important for any website administrator to get an overview of the site visitors. This section aims to introduce the tool that is used to obtain statistics of the iLough-Lab portal traffic and some of its power. The used tool is the *Google Analytics* service (Google Analytics, 2009), a comprehensive web-based, web statistics tool provided by Google. The statistics are shown in a user-friendly graphical display and the service comes with a reporting tool. A Google Analytics



Figure 5.14. Google analytics graphical display showing geographically distributed visits of the iLough-Lab portal. More than 2750 visits from 83 countries were recorded from February 2009 to January 2010.

map overview of the iLough-Lab visitors from the day of its release, 15th February 2009 until 15th January 2010, is shown in Figure 5.14.

The Google analytics service runs on Google servers, hence all data processing and display is not done on the website server, which eliminates any performance loss. The Google analytics reports provide comprehensive information about page hits, page views, average time spent on the website, search engine terms used to find the website, the browser type, the visitors' network location and hostnames etc. An executive summary of the website statistics of Google Analytics is shown in the main interface of the service; this is known as a *dashboard*. Google analytics offer further in-depth specific reports that span over four main categories, visitors' reports, traffic sources, content and goal.

The *visitors' reports* give the user detailed statistics of the site visits. For instance, between 15th February 2009 and 15th January 2010, the following statistics were reported: 2782 visits, 1095 absolute unique visitors, 6928 page views, 2.49 average page views, 00:03:39 average time spent on the website, a 58.23% bounce rate and 38.93% new visits. The visitors' tool can generate benchmark reports comparing the user website with sites of similar size. The user can choose a site category from an available list for comparison. For instance, the closest category for benchmarking the iLough-Lab website is 'Scientific Equipment Sites'. The benchmarking tool reported that the iLough-Lab portal has scored higher in four out of six benchmarking categories. The scores were

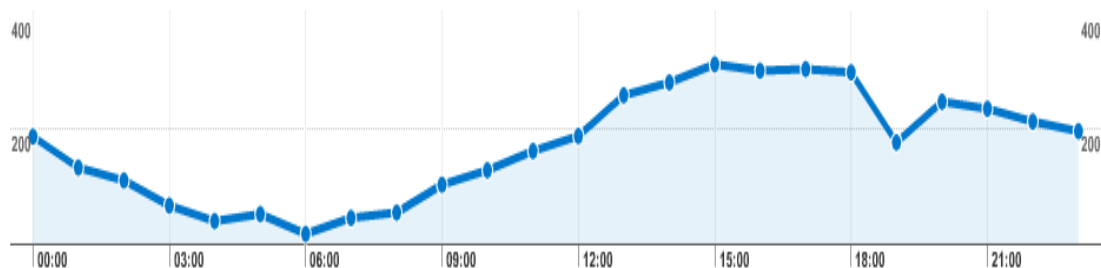


Figure 5.15. Page views per hour for the iLough-Lab portal.

54.53% higher for the visit number, 55.94% higher for the page views, 0.92% higher for the pages per visit and 185.99% higher in the average time spent on the website. The score was less for the new visits and the bounce rate categories. This shows that the iLough-Lab portal has performed relatively better than equivalent sites in attracting visitors.

The visitor trending option gives the user graphic information about the visitors' trends when visiting the website. These graphs can be plotted on an hour, day, week or month basis. It can show information about visits, absolute unique visitors, page views, average page views, time on site and bounce rate. For instance, Figure 5.15 shows the per hour pages views of the iLough-Lab portal; it seems that most views take place between 12:00 and 24:00 with a peak at about 15:00.

Table 5.2. Top five countries ranking by the number of visits to the iLough-Lab portal.

Country	Visits	Pages per Visit
United Kingdom	1802	2.88
United States	265	1.52
Australia	110	2.22
India	92	1.92
Canada	32	1.59

With the *map overlay* option of the visitors' report category, the user obtains statistics about visitors from different countries. For instance, the iLough-Lab portal has attracted visitors from 83 different countries, and the largest number

of visits comes from the United Kingdom, the United States, Australia, India and Canada. The visits statistics of the top five countries are shown in Table 5.2.

The *traffic sources* reports generate statistics about the visitor path to the website, e.g. direct traffic, from referring site, or through a search engine. It can show, for instance, the top sources that lead to the website or the top keywords used in search engines that lead to the website being visited. For instance, 36.44% of the traffic was direct and the rest was through referring sites or search engines. The most referring site is the Engineering Centre for Excellence and Teaching and Learning website (www.engcetl.ac.uk) and the most used search engine is Google.

The *content* category reports generate information about the top viewed content, statistics about the top landing pages, the top exit pages and site overlay statistics. More advanced reports can be generated by the *goal* category after setting goals for conversion observation. These can be used, for instance, as a primary metric for measuring how well a site fulfils business objectives.

The Google Analytics tool provides the remote lab portal administrator with a comprehensive tool for site traffic statistics, such as time of access location of access, and search keywords. These data could be of value for research on remote labs, e.g. the time trend of usage (day or night?), outreach and location of users (national or international?) and time spent on associated material on the site (learning materials, simulations etc.). Such questions are not within the scope of this thesis; nevertheless, this technical chapter has introduced a complementary tool that may help remote lab implementers to obtain the necessary data for targeting such research questions, and sample statistics have been reported to show some of the tool capabilities.

5.6 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 et al., 2002). Learning objects deployment in the teaching and learning process has been found to bring added

positive value to the learning process in many pedagogical studies (Jones and Boyle, 2007).

Many laboratory rigs are multifunctional, offering different experiments for different courses. With a single functioning laboratory rig, different 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 courses 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 and Control 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. A 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 summarised in Table 5.3.

In brief, 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 utilised in an innovative and unconventional manner. The TriLab concept has been presented in Engineering Education (EE2008) and the Global Colloquia on Engineering Education (GCEE2009) conferences (Abdulwahed et al., 2008a; Abdulwahed and Nagy, 2009b).

Table 5.3. 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	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

5.7 Conclusions

This chapter has introduced the TriLab concept, which is a hybrid laboratory model that comprises three components: virtual, hands-on and remote. Detailed explanations of the TriLab model architecture and implementation with LabVIEW have been presented with an implementation case of the TriLab for the Armfield modular rig of the Loughborough Process Control Lab. Following that, a novel web content management system tool in academia, Joomla, was used to develop the remote laboratory portal. The case of developing the iLough-Lab portal with Joomla has been shown. The integration of the Google Analytics tool into the developed portal has been described. This integration allows detailed statistics about visitors, trends and traffic to be obtained, as well as benchmarking the traffic with similar sites. Finally, a discussion of the benefit of the TriLab in increasing the reusability of the laboratory rig has been presented. This chapter aimed to provide a technical model of implementing the TriLab concept for science and engineering academics of little or no previous experience of virtual, hands-on and remote lab integration and web dissemination and statistical data collection.

Chapter 6.

TOWARDS A PEDAGOGICALLY ENHANCED MODEL OF LABORATORY EDUCATION

Overview

This chapter describes a model for laboratory education based on Kolb's experiential learning theory. The method was implemented using components of the TriLab model and has been applied to the teaching of the undergraduate process control laboratory in the Chemical Engineering Department at Loughborough University. The argument that poor learning in the laboratory is due to insufficient activation of the prehension dimension of Kolb's cycle is posed. The experimental design and the data analysis of the laboratory learning outcomes have verified the proposed hypothesis, providing a pedagogical explanation. The quantitative analysis shows significant enhancement of the learning outcomes of the experimental group compared to the control group. The learning outcomes measured by means of pre- and post-lab tests were consistent over two academic years. Apart from the hands-on session, the proposed model involves additional activities, such as pre- and post-lab tests and virtual laboratory sessions. These activities are associated with Kolb's cycle to facilitate constructivist learning. The survey of the students' opinion of the process control lab has shown a positive attitude. This chapter represents the first laboratory education model that builds thoroughly on Kolb's experiential learning theory together with empirical analysis.

6.1 Introduction

The literature on laboratory education lacks significant contributions of empirical quantitative studies (Ma and Nickerson, 2006); this is discussed comprehensively in Chapter 3. Furthermore, it is seldom one finds a pedagogically informed model of conducting laboratory education, in particular the case of integrating virtual and/or remote modes with the hands-on mode. In this chapter, poor learning outcomes of laboratory education are investigated and a pedagogical explanation is sought by means of Kolb's experiential learning theory and empirical data analysis of laboratory learning outcomes. A new approach to laboratory education is described based on the findings. This

approach is solely underpinned by Kolb's experiential learning theory (Kolb, 1984). The method uses a combination of virtual, hands-on and remote laboratory modes together with pre- and post-lab tests. The aim is to improve information retention and constructivist learning by students by activating the stages of Kolb's learning cycle. The study was applied over two academic years, 2007-2008 and 2008-2009, during the teaching of second year undergraduates in the Process Control Laboratory of the Chemical Engineering Department at Loughborough University, United Kingdom.

6.2 Pedagogical Hypothesis of Explaining Poor Outcomes of Hands-on Laboratories Based on Kolb's Theories

It is hypothesised in the light of Kolb's experiential learning theory, introduced in Chapter 3, that *the poor learning outcome of laboratory sessions that is frequently reported in the literature could be related to weak activation of the prehension dimension before coming to the lab*. Hence, the lab session turns into an algorithmic following of the lab manual instead of actively constructing meaningful knowledge from it.

In this chapter, it is proposed that *using the Virtual Lab in a preparation session can lead to better activation of the prehension dimension in Kolb's cycle, which then yields better activation of the transformation dimension*.

To verify this hypothesis, a pedagogical experimental procedure was designed and applied in the second year module Instrumentation, Control and Industrial Practice. The verification procedure comprises *two main phases*. The first phase is to *verify whether intervention (preparation with a virtual lab) leads to better activation of the prehension dimension of Kolb's cycle*. The second phase is to *verify whether the success of the first phase leads to better activation of the transformation dimension*. Further details of the methodology and the experimental procedures will follow later in this chapter.

6.3 The Virtual Lab in a Preparation Session

Laboratory preparation can be conducted in many ways. For instance, students can be asked to prepare by reading the instructions in the lab manual and developing an experimental procedure. Alternatively, the lab manual preparation can be combined with a simulated version of the lab (virtual lab). The lab manual + virtual lab preparation can result in enhanced preparation for many reasons.

According to the dual coding theory of information cognition, the human mind perceives and stores verbal and visual information through two distinct channels (Clark and 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 visualise 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: read/write, visual, aural and kinaesthetic (VARK, 2009). 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 visualises 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, as discussed in Chapter 3. Additionally, the use of virtual labs provides an ideal framework for inducing reflection during preparation and hence enhancing, according to Kolb's model, conceptualisation and achieves some learning during the preparation for the lab.

This chapter provides a pedagogically informed utilisation of the TriLab model (in particular the use of the virtual lab for preparation) of second year students in the Process Control Laboratory in the light of Kolb's experiential learning theory. This is based on a comprehensive empirical analysis of the data by utilizing statistical methods that are typically used in quantitative educational research. These methods are introduced in the next section.

6.4 Statistical Methods in Educational Research

Most of the data in this chapter, e.g. means of tests, is analysed by means of inferential statistics.

This section aims to introduce the statistical methods that are used in Chapter 6 and 7 for data analysis purposes. In quantitative educational research, comparing means cannot be done simply by observing which is bigger or smaller. For instance, let us consider a new teaching method to be applied to a sample of students (experimental group) that is similar to another sample of students (control group), which follows a classical teaching approach. Looking at merely whether the mean of the experimental group differs from the mean of the control group does not reveal whether the difference is due to the different teaching approach or is just due to chance. Statistical analysis tools provide researchers in the social sciences with the means for in-depth analysis of the data. In particular, the parametric and non-parametric tests for comparing means are widely used in educational research (Cohen et al., 2005).

6.4.1 Comparing Means; the Null Hypothesis

Comparing the means of two independent samples starts with a hypothesis that assumes that there is NO statistically significant difference in the means. In statistics, the only way to support a true hypothesis is by rejecting its opposite. It is commonly agreed among the statistics community that it is impossible to prove that something is true, but it is possible to show that something is false (Howell, 1999).

This is why statistical hypothesis testing is usually achieved through laying down a 'Null Hypothesis' which is of opposite meaning to the intended hypothesis for testing. The null hypothesis is so called because it states normally that: "... there is no difference (or null) between the control and the tested groups". When the null hypothesis is proved false, the intended hypothesis for study would be perceived as a true (Conover, 1998). There are many statistical methods for testing whether a null hypothesis is true or false; this approach is normally referred to as *inferential statistics*.

6.4.2 The Hypothesis Tests, Type I and Type II Errors

Hypothesis tests are classified into two categories: parametric tests such as the t-test and non parametric tests such as Mann-Whitney U test. Parametric tests require the valid assumption of the data to be tested; in particular, they assume normally distributed data (Cohen et al., 2005). On the other hand, non-parametric tests do not require such conditions and hence they are more applicable than parametric tests when information about the data distribution is not available or when the data is not normally distributed (Cohen et al., 2005).

Using a non-parametric test instead of a parametric test is recommended when the sample number is small (Conover, 1998).

The null hypothesis is normally rejected if the statistical test has resulted in a probability of 95% or more that the difference is NOT due to random chance. This is expressed by a significance value of 0.05 or less and is referred normally in the literature as the *p-value*. The 0.05 value has been historically suggested as arbitrary, but it is accepted as a standard among the statistical community. A historical review on this issue is provided by Dallal (2003). If the threshold (*p-value*) is lowered, e.g. to 0.02, this will result in a greater confidence in accepting or rejecting the null hypothesis test results.

Such a low value minimises a so-called ‘Type I error’, where the null hypothesis is rejected while it is in fact true. However, low *p-values* may result in a so-called ‘Type II error’, where the null hypothesis is not rejected when it is in fact false. When the sample number is small, it may be recommended to consider a *p-value* threshold of 0.10 to avoid a Type II error (Cohen et al., 2005). In this study, the standard *p-value* threshold of 0.05 is admitted. Nevertheless, in some cases, a 0.1 value will be pointed out as a potential threshold when the sample number (*N*) is small (e.g. $N \leq 15$) to avoid Type II errors.

6.4.3 The Mann-Whitney U and Wilcoxon Non-Parametric Tests

The Mann-Whitney U test is a non-parametric test that can be used to determine whether two independent groups of sampled data are different or not. For instance, the Mann-Whitney U test can be used to find the statistical significance of the difference between two groups’ responses to a question. The Wilcoxon test is a non-parametric test similar to the Mann-Whitney U test; however, it operates on data obtained from one group. For instance, the Wilcoxon test can be used to obtain the statistical significance of the difference between a group’s response to different questions.

The methodology of calculating the Mann-Whitney U and Wilcoxon tests can be found in classical statistics textbooks (see Conover, 1998). The numerical procedures for conducting statistical tests can be cumbersome and time consuming. However, statistical packages such as SPSS include built-in algorithms for facilitating such calculations (Cohen et al., 2005).

6.5 Outline of the Methodology for the Pedagogical Effectiveness Measurement

To measure the difference in learning outcomes as a result of using the virtual lab component of the TriLab model in a pre-lab session, the students were divided into two groups: control and experimental. In quantitative educational research, the term ‘control group’ normally refers to the group of students for which the classical or standard approach of teaching and learning is applied, while the term ‘experimental group’ refers to the group of students for which the new approach of teaching and learning (treatment) is applied.

The students of the control group were aimed to conduct the laboratory experiments in the classical way, e.g. only conducting a hands-on session. The students of the experimental group were aimed to follow a new approach where they attend a preparation session before the lab session using a virtual version.

The learning outcomes are measured by means of pre- and post-lab tests. Quantitative analysis of the results has been used to determine whether or not there are statistically significant differences in the learning outcomes between the students of the control and the experimental groups. Further analysis investigates the marks of the laboratory reports and the final exam of the module. For the evaluation of the statistically significant difference, the *null hypothesis* is used. The null hypothesis in this case states that: “There is no

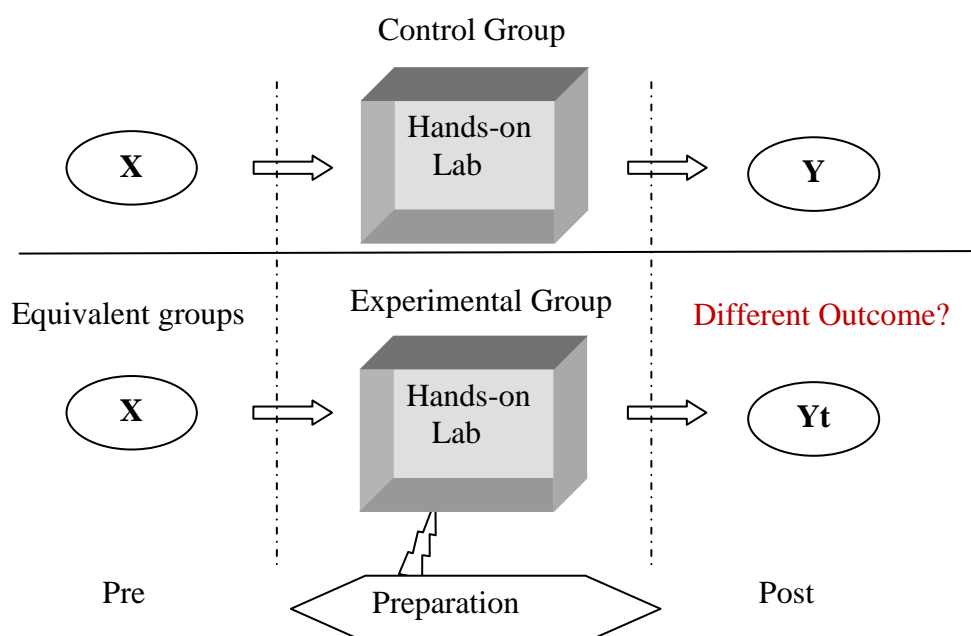


Figure 6.1. Conceptual model of the pedagogical experimentation methodology.

statistically significant difference in the learning outcome between the control group and the experimental group". To accept or reject the null hypothesis, non-parametric tests are used. In most cases, the null hypothesis is rejected (meaning that there is a statistically significant difference between the data) if the p-value of the test is less than 0.05. Figure 6.1 shows a generic conceptual model of the pedagogical experimentation methodology, where X represents the equivalent groups (control and experimental before treatment) and Y and Y_t are the learning outcome results from the control and the experimental groups after treatment respectively. All students were informed that the pre- and post-lab tests as well as the preparation session were not compulsory. The students were also informed that the pre- and post-tests were being conducted for educational research purposes and that the marks were confidential and not part of the official assessment of the laboratory coursework.

Students were also surveyed for their opinion of the Process Control Lab. The findings are reported by means of descriptive and inferential statistics. Further information about the methodology, the used instruments and the statistical analysis are detailed where specific in this chapter. The next subsection details the process of selecting the control and experimental groups.

6.5.1 Selection of the Control and Experimental Groups

The number of students registered 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 organised 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 organised 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.

6.5.2 Logistical and Ethical Issues in the Experimental Design

Logistical and ethical aspects of the pedagogical experimental design are important to analyse to understand the rationale behind the design process. To make the pre-lab preparatory sessions compulsory would require changes in the course structure, which must be approved by the Departmental and University Teaching Committees and could violate the generic recommendations related to the number of contact hours within a module. The extra hours required for compulsory preparatory sessions would be possible officially only by reducing the number of lectures or problem classes. Not making the virtual laboratory software available to the control group raised ethical issues related to discrimination in using teaching aids for parts of the class. This was also partially the reason that in the preparatory session minimal supervision and help was offered.

To overcome the logistical and ethical constraints, the educational experimentation was designed so that no pre-lab preparatory sessions were scheduled for groups $G1$ and $G2$. However, they were asked to prepare for the lab. The initial intention in the design of the pedagogical experiments was that the control group would prepare by reading the manual and the experimental group by using the virtual lab and the manual. However, to eliminate ethical issues, the lab manual and the virtual lab software were made available for students to download and use in their preparation. Non-compulsory pre-lab sessions were scheduled for the $G3$ and $G4$ students. These were timetabled internally in a way that eliminated conflicts with the students' other duties as much as possible.

About 60% to 70% of the students of $G3$ and $G4$ responded to the request to attend the preparation session each time, forming the experimental group. The average mark 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 ($p\text{-value} = 0.298 > 0.05$ for the 2007-2008 academic year and $p\text{-value} = 0.51 > 0.05$ for the 2008-2009 academic year), indicating that the control and the experimental groups are very similar in regard with the previous year academic achievement.

6.6 Pre- and Post-Lab Tests; Instruments of the Verification Stages of the Pedagogical Hypothesis

The verification was divided into two main parts: (1) verifying that the virtual lab can lead to enhanced activation of the prehension dimension, and (2) verifying that this leads to better activation of the knowledge transformation dimension. For the verification of the prehension dimension activation, pre-lab tests (lasting for 15 minutes on average) were designed and were conducted just before starting the hands-on session. The pre-lab tests were given to students in Week 1 and Week 2. Samples of the pre-lab tests of Week 1 and Week 2 are shown in Appendix 4 and Appendix 5 respectively. The statistically significant differences between the answers of the students from the control and the experimental groups indicate that a pre-lab session with a virtual lab plays a role in grasping needed information for the hands-on laboratory session. Similarly, to verify whether enhanced activation of the knowledge transformation axis of Kolb's cycle took place, post-lab tests (lasting for 15 minutes on average) were conducted directly after the students finished the hands-on lab session. Hence, 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. Figure 6.2 shows a conceptual model of the hands-on lab session's progress with pre- and post-lab tests. Samples of the post-lab tests can be found in Appendix 7 and Appendix 8, for Week 1 and Week 2 respectively.

The tests were designed in correlation with the laboratory objectives and in discussion with the course lecturer. The Week 1 lab session aimed to provide the students with hands-on experience of calibrating and deriving the characteristics of the water level sensor and the control valve. Alongside the session, the students were meant to familiarise themselves with the lab rig components and their interconnections in forming a control system. The pre-lab test of Week 1

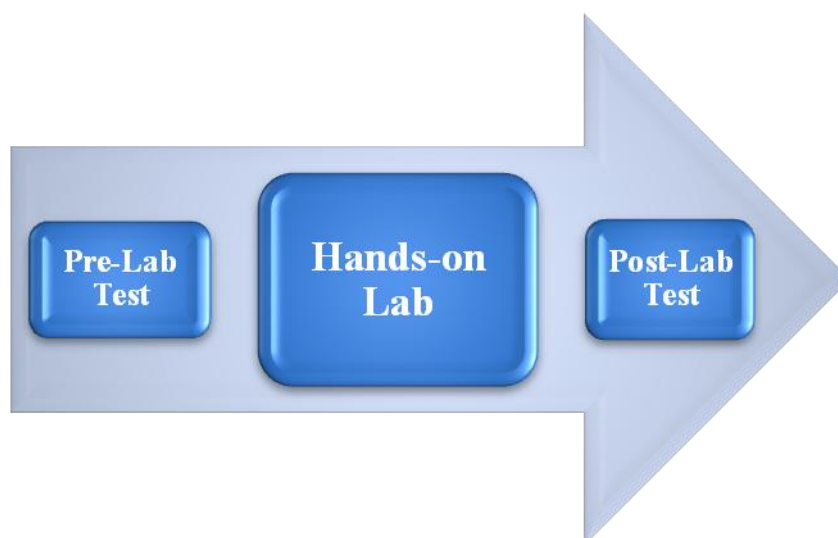


Figure 6.2. The hands-on laboratory session progress. The total session duration is three hours. Students work on a pre-lab test during the first 15 minutes, then proceed to conduct the hands-on lab experimental procedure as specified in the lab manual. Once they finish, they have to complete a post-lab test for about 15 minutes before leaving.

consisted of seven questions. The test aimed to examine the students' understanding of the procedure they should follow for calibrating the level sensor (Question 1) and the control valve (Question 2). Both of these questions need good elaboration to answer since the procedures are non-trivial for novices. Figure 6.3 shows Question 1 of the pre-lab test of Week 1. The remaining questions (Question 3 to Question 7) aimed to test the students' understanding of different components of the process and its functionality (e.g. what is a sensor?). These were rather simple questions and a quick reading of the manual or common engineering sense could lead to the correct answer. The post-lab test of Week 1 consisted of 10 questions. The first two questions were the main ones, where the students have been asked to sketch a rough curve of the level sensor and the control valve characteristics. Figure 6.4 shows Question 2 of the post-lab test of Week 1. The remaining questions tested the students understanding of the process, e.g. Question 6: When the process is set to automatic mode, what is the controller?. Question 7 and the Question 8 test the students' ability to detect open- and closed-loop processes with an explanation; hence, they particularly needed a good conceptual understanding of the process operation to answer correctly. The Week 2 session of the Process Control Lab is of a relatively of open-ended nature and its focus is on qualitative understanding of PID control. Hence the pre- and post-lab tests of Week 2 were mainly qualitative questions and no procedural questions similar to Questions 1 and 2 of the pre- and post-lab tests of Week 1 were included. Further discussion of the pre- and post-lab tests is provided where appropriate alongside the data

Pre Lab quizzes for week 1:

- 1- Describe the experimentation procedure you are going to follow for the sensor calibration.

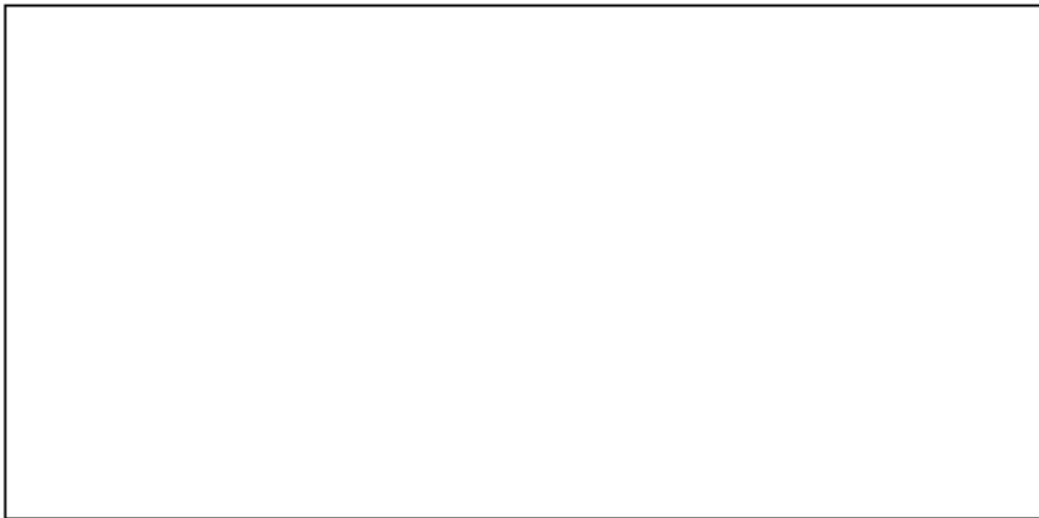


Figure 6.3. A key question of the pre-lab test of Week 1. Students are asked to describe the sensor calibration procedure.

- 2- Have a quick look on the control valve calibration measurements and draw roughly the control valve characteristics.



Figure 6.4. A key question of the post-lab test of Week 1. Students are asked to sketch a rough curve of the control valve characteristic.

analysis sections of the tests later in this chapter. Questions from the pre- or post-lab tests will be referred to as Q followed by its number throughout this chapter, e.g. Q6 refers to Question 6.

6.7 Analysis of Activation of the Prehension Dimension (Knowledge Grasping) of Kolb's Cycle

The analysis of the activation of the knowledge-grasping dimension of Kolb's cycle depends on the analysis of the results of the pre-lab tests of Week 1 and Week 2. The tests of the statistical significance differences revealed p-values < 0.05 for the total mean of the pre-lab tests of both Week 1 and Week 2 in both academic years 2007-2008 and 2008-2009. This clearly indicates that using a virtual lab in a preparation session has helped to activate the prehension dimension of Kolb's experiential learning cycle. Further details of the analysis and the results are provided in the following subsections.

6.7.1 Week 1 Laboratory Session

The results of the evaluation of the pre-lab test of Week 1 for the academic year 2007-2008 revealed that the experimental group' students scored higher than the control group' students in the majority of the questions, as shown in Figure 6.5. Using the Mann-Whitney U test, the p-values of the differences between the answers of the students of the control and experimental group, for Q1 and Q2 (strongly related to the experimental procedure) were smaller than 0.05, indicating that the null hypothesis can be rejected. Hence, there is strong statistical evidence that exposing the students to a preparatory session using the virtual laboratory led them to an overall enhanced grasp of the procedural tasks needed for performing in the lab.

All students were asked to prepare for the lab; the software and the lab manual were available to download from the Web. The poorer results of the control group could be because those students may only have read the manual and had not (or had poorly) experienced the procedure with the virtual lab compared to the experimental group students. The difference between the control and the experimental groups is less significant (p-value = $0.116 > 0.05$ for the 2007-2008 academic year) for the sum of the questions Q3 to Q7 (i.e. questions that are less related to the experimental procedure). However, the average mean is still higher for the experimental group. A summary of the p-values for the questions in the pre-lab test for Week 1 of the academic year 2007-2008 is shown in Table 6.1. The level sensor calibration procedure (asked about in Q1) is relatively easier than the procedure for the control valve calibration (asked about in Q2). This may explain the higher mean of Q1 compared to Q2.

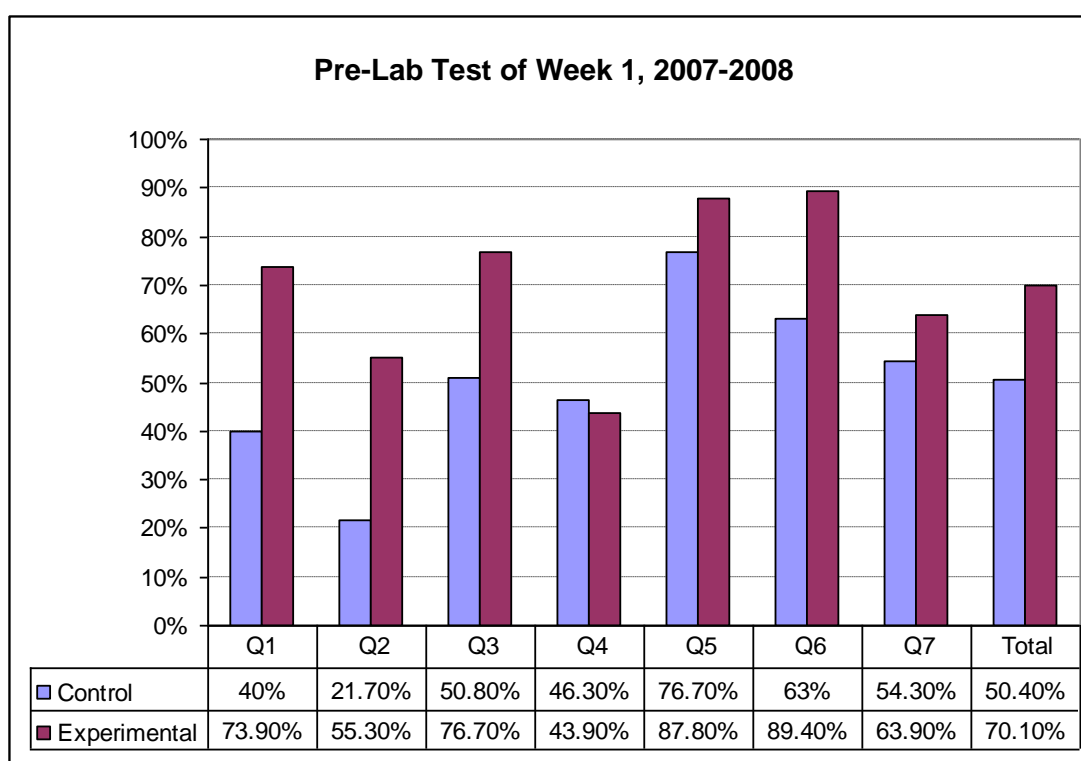


Figure 6.5. Individual means of the questions of the pre-lab test of the Week 1 laboratory session of the 2007-2008 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

Table 6.1. Pre-lab test results of Week 1 (2007-2008).
Number of samples (control/experimental) is 30/18.

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.002
Q2	0.002
Q3	0.013
Q4	0.794
Q5	0.723
Q6	0.104
Q7	0.759
Sum Q3 to Q7	0.166
Sum Q1 to Q7	0.009

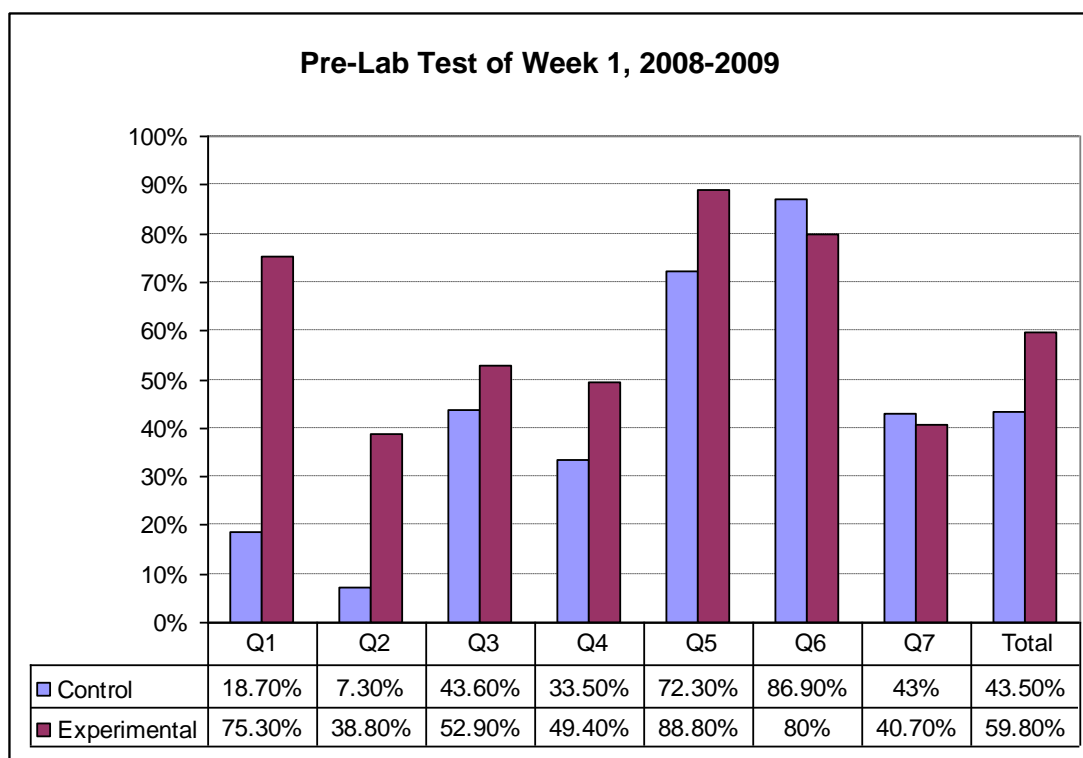


Figure 6.6. Individual means of the questions of the pre-lab test of the Week 1 laboratory session of the 2008-2009 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

**Table 6.2. Pre-Lab test results of Week 1 (2008-2009).
Number of samples (control/experimental) is 26/17.**

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.000
Q2	0.000
Q3	0.183
Q4	0.162
Q5	0.068
Q6	0.662
Q7	0.183
Sum Q3 to Q7	0.261
Sum Q1 to Q7	0.004

The analysis of the results of the pre-lab test for Week 1 of the 2008-2009 academic year, as shown in Figure 6.6 and Table 6.2, revealed an outcome consistent with the previous academic year's analysis. This shows that students of the experimental group had better activation of the prehension dimension of Kolb's cycle as they could grasp the knowledge needed for the hands-on lab operation via the virtual lab.

6.7.2 Week 2 Laboratory Session

The experimental group students obtained higher means in the majority of the questions of the pre-lab test for Week 2 of the academic year 2007-2008, as shown in Figure 6.7. The total mean average of the test was higher for the experimental group than for the control group, and the statistical significance was smaller than the threshold of 0.05 (p -value = 0.041), allowing us to reject the null hypothesis; the p -values of the individual questions are shown in Table 6.3. The pre-lab test for Week 2 for the 2008-2009 academic year revealed a similar outcome, where the mean of the experimental group was higher than for the control group, and the p -value was 0.001. The detailed results are shown in Figure 6.8 and Table 6.4.

The first three questions were rather general, whereas the remainder of the questions was strongly related to the experiment in Week 2. For instance, any student who attended the Week 1 lab session should have been able to answer Q1, which is strongly related to the rig operation. The means of both groups were very similar for this question. Question Q2 has a short answer; the students are asked to indicate what the term PID stands for. The experimental group's mean was higher than the control group for both years. In 2007-2008, the p -value was not in the threshold domain, but in 2008-2009 it was 0.001 and the mean difference was higher. Q3 is a more theoretical question that tests the students' understanding of how the PID controller works. The means of the experimental group was higher for both academic years 2007-2008 and 2008-2009, however the p -value did not reveal statistical significance. Q4 is strongly related to the experiment, and asks the students to evaluate the process behaviour given a defined set of PID controller parameters. The means of the experimental group were considerably higher for this question, with strong statistical significance for both academic years 2007-2008 and 2008-2009. Q5 is also related to the experiment; however for students to answer this question correctly, they must have done the preparation using the whole manual, as this question is related to the last section of the experiment. During the one-hour preparation session, many of the students of the experimental group had not reached that stage.

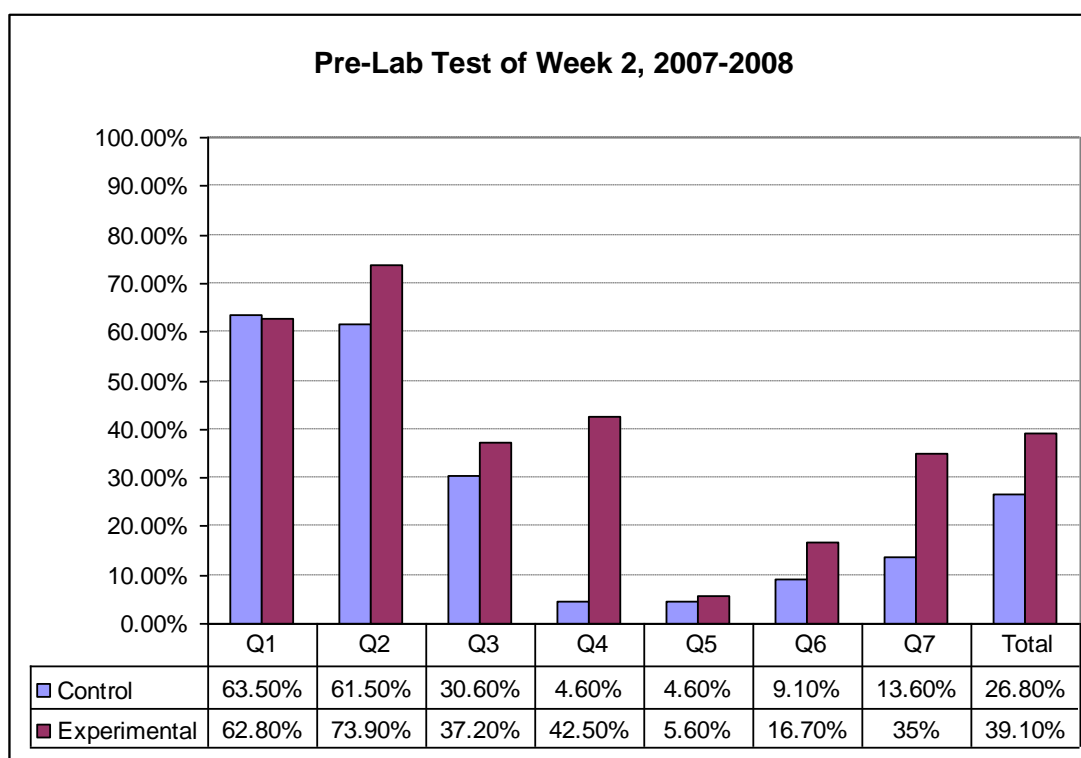


Figure 6.7. Individual means of the questions of the pre-lab test of the Week 2 laboratory session of the 2007-2008 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

**Table 6.3. Pre-Lab test results of Week 2 (2007-2008).
Number of samples (control/experimental) is 33/18.**

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.866
Q2	0.369
Q3	0.793
Q4	0.001
Q5	0.961
Q6	0.427
Q7	0.031
Sum Q1 to Q7	0.041

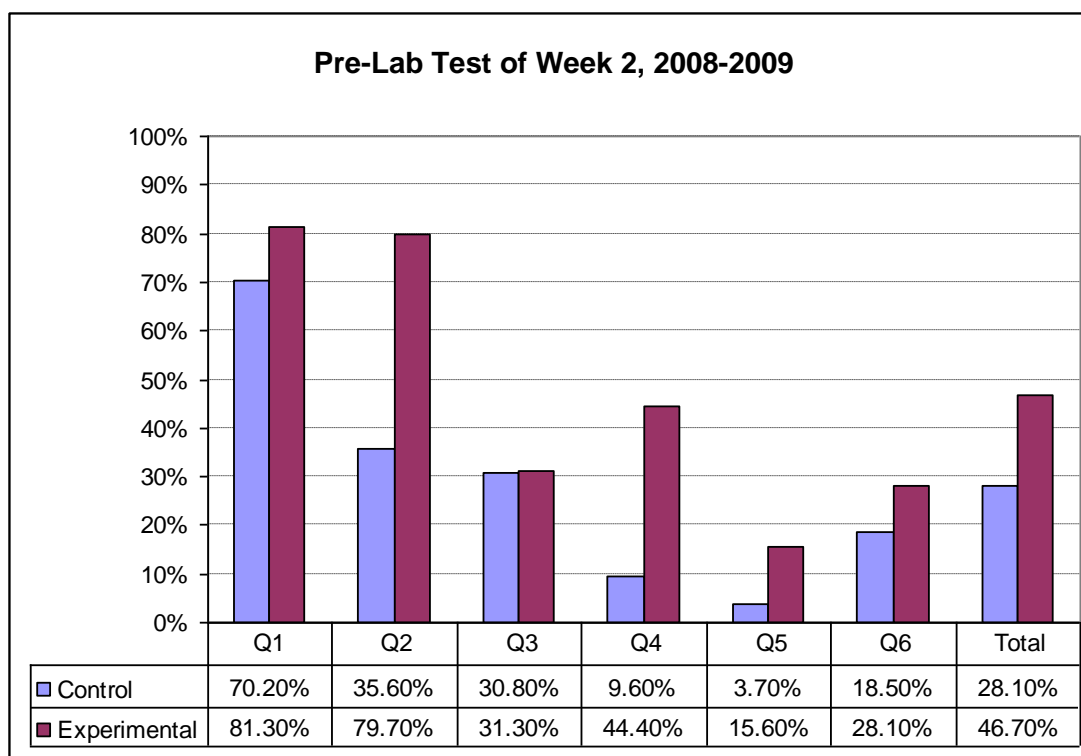


Figure 6.8. Individual means of the questions of the pre-lab test of the Week 2 laboratory session of the 2008-2009 academic year. The experimental group students scored higher than the control group students in all questions.

**Table 6.4. Pre-Lab test results of Week 2 (2008-2009).
Number of samples (control/experimental) is 26/17.**

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.337
Q2	0.003
Q3	0.432
Q4	0.010
Q5	0.110
Q6	0.392
Sum Q1 to Q6	0.001

This is very probably because they did not continue to finalise their preparation after the session. This may explain the low mean value of the experimental group, which is nevertheless higher compared to the control group. Q6 is difficult to answer without a very good understanding of the theory. The mean of the experimental group was higher, but without strong statistical evidence, as the p-value was higher than the threshold for both academic years. Question Q7 is of the same nature as Q4. Students of the experimental group showed a greater ability, with strong statistical evidence, to answer this question correctly. This question was eliminated in the 2008-2009 pre-lab tests, and was instead used in the post-lab test (Q1 in Appendix 9).

Table 6.5. Pre-Lab test answering attempt frequency of Week 2 (2007-2008).
Number of samples (control/ experimental) is 33/18.

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test	Means % (Control/ Experimental)
Set 1	0.850	88.7/89.0
Set 2	0.000	30.5/79.3

Table 6.6. Pre-Lab test answering attempts frequency of Week 2 (2008-2009).
Number of samples (control/ experimental) is 26/17.

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test	Means % (Control/ Experimental)
Set 1	0.255	82.7/89.7
Set 2	0.000	31.0/79.3

In another measure, shown in Table 6.5 and Table 6.6, the frequency of attempts to answer the first set of questions (Q1, Q2,Q3) vs. the second set (Q4, Q5,Q6, Q7), i.e. the general set vs. the experiment-related set, shows that the students' attempts were almost identical for the first set. However, there is statistically significant evidence that the experimental group students were more willing to attempt to answer the second set, which is strongly related to the experiment. This indicates that the pre-lab session stimulated the experimental group students to think and reflect on the task related to the experiment in Week 2

more than the control group students. The p-value was 0.000 in both academic years 2007-2008 and 2008-2009.

6.8 Analysis of the Activation of the Knowledge Transformation Dimension of Kolb's Cycle

Post-lab tests were conducted directly after the students finished their experiments for both the control and the experimental groups in the Week 1 and Week 2 lab sessions. This aimed to verify that better activation of the prehension dimension leads to better knowledge transformation into mental models (Kolb, 1984) after the hands-on lab session. The experimental group students achieved higher means in the post-lab tests of Week 1 and Week 2 in both academic years 2007-2008 and 2008-2009. The Mann Whitney U tests of the statistical significance differences in the means between the students of the control and experimental groups revealed p-values < 0.05 for the total average of the post-lab tests of both Week 1 and Week 2 and in both academic years 2007-2008 and 2008-2009. This indicates clearly that better activation of the prehension dimension led to better activation of the knowledge transformation dimension of Kolb's experiential learning cycle. Further details of the analysis and the results are provided in the following subsections.

6.8.1 Week 1 Laboratory Session

The students of the experimental group achieved higher means in the majority of the questions of the post-lab test of Week 1 (shown in Appendix 7) for both academic years, with a statistically significant p-value for the total mark of the test, as shown in Figure 6.9 and Figure 6.10, and Table 6.7 and Table 6.8. In question Q1 of the post-lab test of Week 1, the students were asked to create a qualitative plot of the level sensor characteristic curve based on their observations and the data they had collected during the experiment.

The level sensor characteristics are represented by a simple linear curve with no hysteresis. The students' answers were rather close for both the experimental and the control groups. The p-value for Q1 is 0.302, which is larger than the threshold of 0.05, indicating that there is no statistically significant difference between the control and the experimental groups. In question Q2, the students were asked to plot the control valve characteristic, which is nonlinear and shows hysteresis.

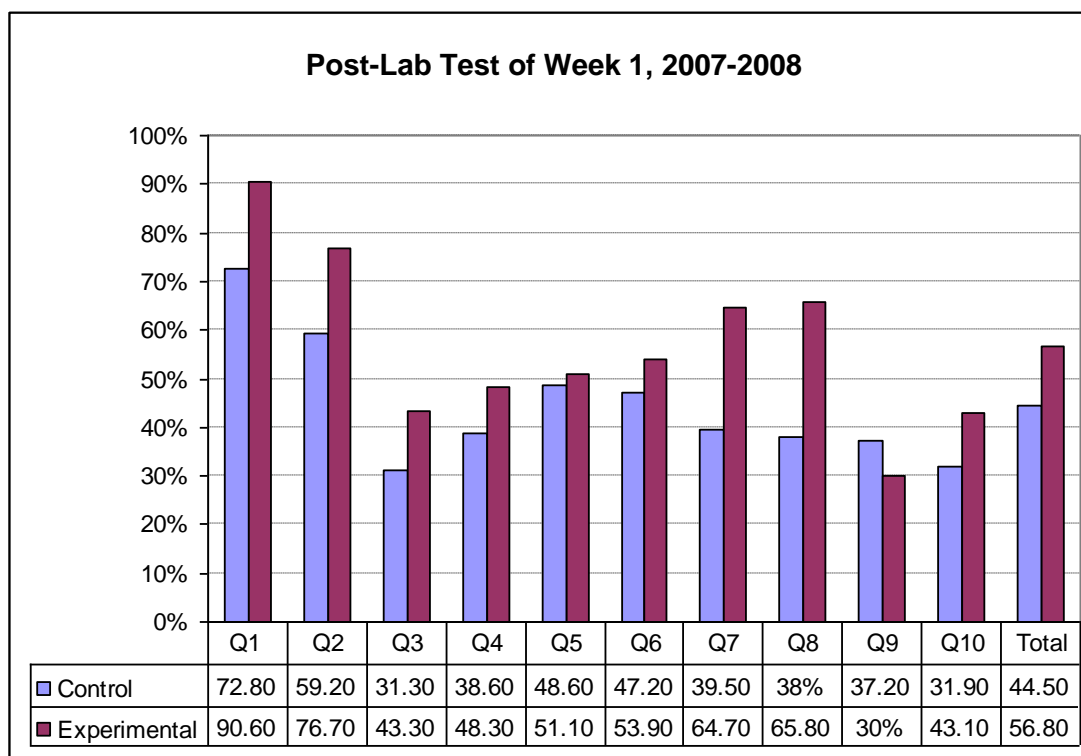


Figure 6.9. Individual means of the questions of the post-lab test of the Week 1 laboratory session of the 2007-2008 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

**Table 6.7. Post-Lab test results of Week 1 (2007-2008).
Number of samples (control/experimental) is 32/18.**

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.302
Q2	0.025
Q3	0.257
Q4	0.498
Q5	0.847
Q6	0.829
Q7	0.034
Q8	0.026
Q9	0.543
Q10	0.211
Sum Q1-Q10	0.031

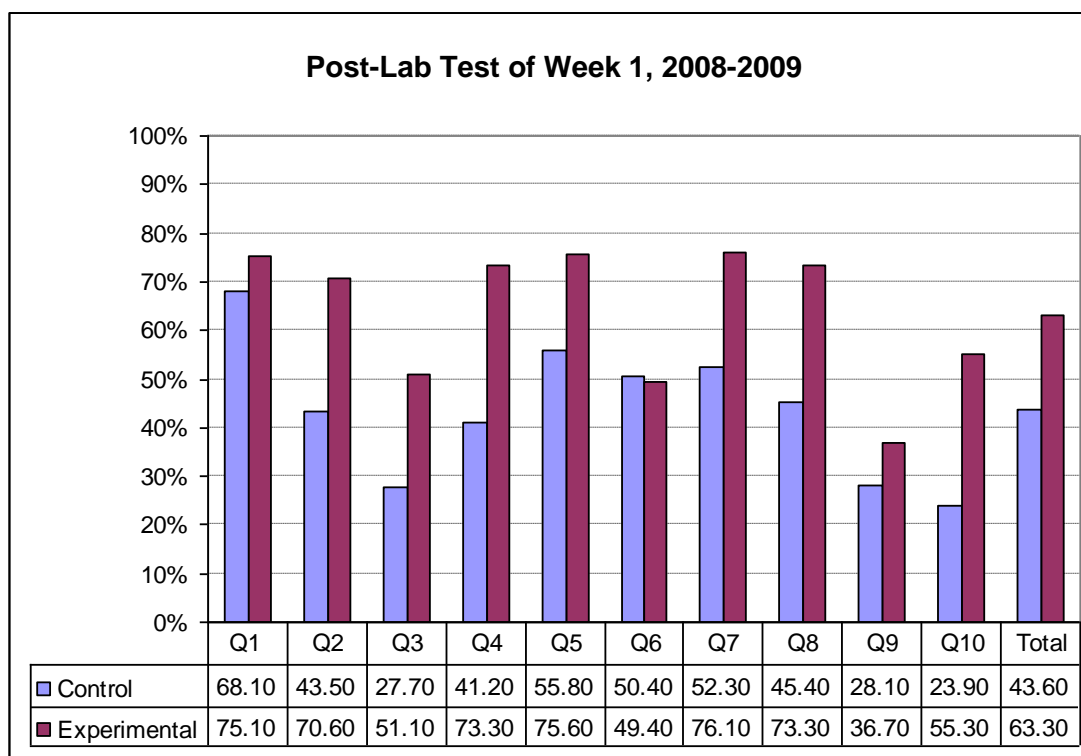


Figure 6.10. Individual means of the questions of the post-lab test of Week 1 laboratory session of the 2008-2009 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

**Table 6.8. Post-Lab test results of Week 1 (2008-2009).
Number of samples (control/experimental) is 26/18.**

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.671
Q2	0.012
Q3	0.042
Q4	0.007
Q5	0.272
Q6	0.794
Q7	0.048
Q8	0.021
Q9	0.587
Q10	0.008
Sum Q1-Q10	0.008

A significantly larger portion (more than double) of the experimental group students could distinguish these features (which requires greater in-depth analysis of the data), whereas fewer of the control group students discovered the hysteresis. The p-value of Q2 is $0.025 < 0.05$ in the 2007-2008 academic year, hence the null hypothesis can be rejected. For the other questions (Q3-Q6, Q9 and Q10), which are rather general, the students from the control and the experimental group showed a close outcome. Questions 7 and 8 were purely conceptual, testing the students' understanding of open and closed loop systems. The students from the experimental group performed overall much better in these questions than students from the control group. It deserves mentioning that the simulation of the control valve in the virtual lab is not identical to the real behaviour of the physical control valve in the test rig. The simulated control valve has linear characteristics and no hysteresis, hence these features were not observed by the experimental group students in the preparation session. Nevertheless, they showed a greater ability to detect these features than the students from the control group. The results of the 2008-2009 academic year were very consistent with the previous year's findings with regards to Q1, Q2, Q7, Q8 and the total mean average of the test.

6.8.2 Week 2 Laboratory Session

The post-lab test of Week 2 shows a higher mean for the experimental group students compared to the control group in both academic years 2007-2008 and 2008-2009. The overall average of the post-lab test for 2007-2008 yielded a statistically significant difference, with a p-value = $0.045 < 0.05$. Figure 6.11 shows the means of the post-lab test of Week 2 for the 2007-2008 academic year. The score yielded a significant statistical value, leading us to reject the null hypothesis (p-value = $0.022 < 0.05$). Hence, it can be concluded that in general there is statistically significant evidence that the experimental group students scored higher than the control group students in the post-lab test of Week 2 as a result of the virtual lab preparation session leading to better activation of the knowledge transformation dimension. Table 6.9 shows the p-values of the individual questions and the total average of the test.

The post lab test in the 2008-2009 academic year was extended from 3 questions to 10 questions. In general, the scores of the experimental group were higher in most questions (except Q1 and Q3) than the scores of the control group as shown in Figure 6.12. The statistical significance varied between significant and non-significant for the individual questions as shown in Table 6.10.

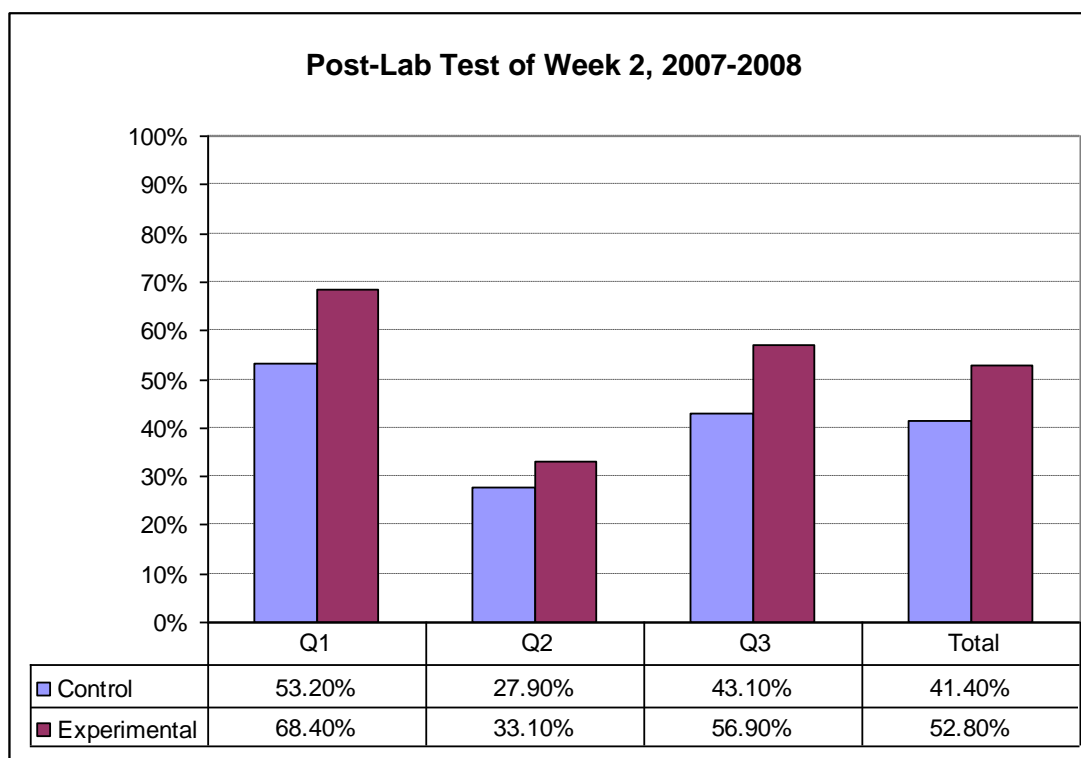


Figure 6.11. Individual means of the questions of the post-lab test of the Week 2 laboratory session of the 2007-2008 academic year. The experimental group students scored higher than the control group students in all questions.

Table 6.9. Post-Lab test results of Week 2 (2007-2008).
Number of samples (control/experimental) is 34/16.

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.013
Q2	0.469
Q3	0.154
Sum Q1 to Q3	0.045

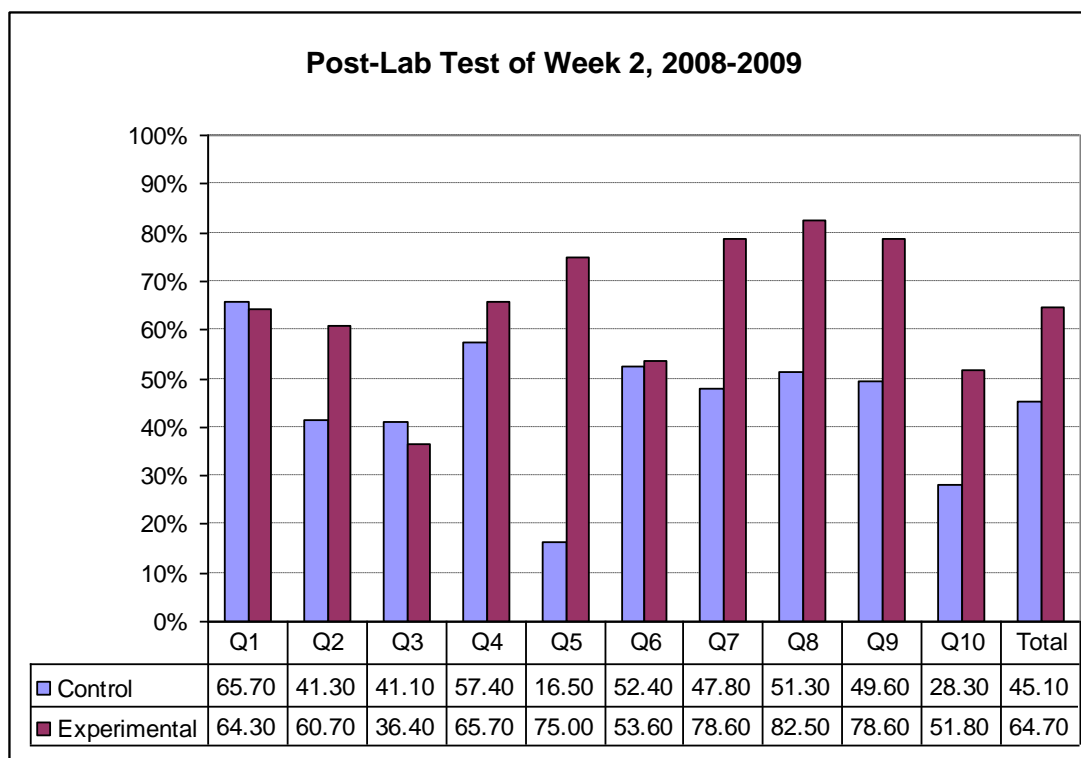


Figure 6.12. Individual means of the questions of the post-lab test of the Week 2 laboratory session of the 2008-2009 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

**Table 6.10. Post-Lab test results of Week 2 (2008-2009).
Number of samples (control/experimental) is 23/14.**

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test
Q1	0.889
Q2	0.219
Q3	0.793
Q4	0.486
Q5	0.001
Q6	0.793
Q7	0.071
Q8	0.024
Q9	0.057
Q10	0.147
Sum Q1-Q10	0.022

6.9 The Impact of Activating the Dimensions of Kolb's Cycle on the Marks of the Laboratory Report

The direct measurements of the impact of activating Kolb's cycle have been conducted via pre- and post-lab tests, as shown earlier. In a less direct measurement, the impact on the lab reports of the students was investigated. For this purpose, to maximise the sample number, the control and experimental groups of both academic years were grouped together, resulting in a sample number of 65/46 (control/experimental). All students had to submit a 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.

6.9.1 Details of the Laboratory Report Structure

The Summary should provide the main purpose of the report and a brief overview of the most important findings. The Introduction is meant to provide a short motivation (one page maximum) of the importance of understanding process dynamics and control. In the Theory section (2-5 pages), the students should explain in a few sentences the theoretical background related to: 1- how the sensor works; 2- calibration; 3- how the control valve works; and 4- PID control. The students should provide their own description, and not simply copy from the lab manual, with references demonstrating their readings about the topics. The Experimental Procedure (2-4 pages) should provide a brief summary of the procedure and methodology they used in obtaining the measurements. A proper P & ID of the experimental rig (showing all elements and instruments) must be provided using standard symbols for instrumentation. The Results and Discussions section (6-10 pages) should show all the results requested in the lab manual. This should contain as a minimum: results from the level calibration; analysis of hysteresis; valve calibration; calculation of the relative control valve resistance; figures for and discussion of manual control; results on heuristic tuning; automatic tuning and the effect of controller signs. The students should compare/contrast and analyse their results and not only show figures with simple plots. Students should make sure that the controller tuning parameters

are indicated for different parts of the figure and they should correlate the dynamic response in their discussion with the changes in the parameters. In the Conclusions, a brief statement (about half a page) with the main results and conclusion of the report should be provided.

6.9.2 Marking the Laboratory Report

Marking was based on how well the report was organised in the light of the given structure, the correctness of the P & ID diagram, 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. The laboratory report marks were analysed to check if there were statistically significant differences between the control and experimental groups. The next section provides the analysis and the findings.

6.9.3 Analysis of the Marks of the Laboratory Report

For further in-depth analysis, 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 outcomes of the laboratory sessions.* This can be explained by the fact that in the second half of the

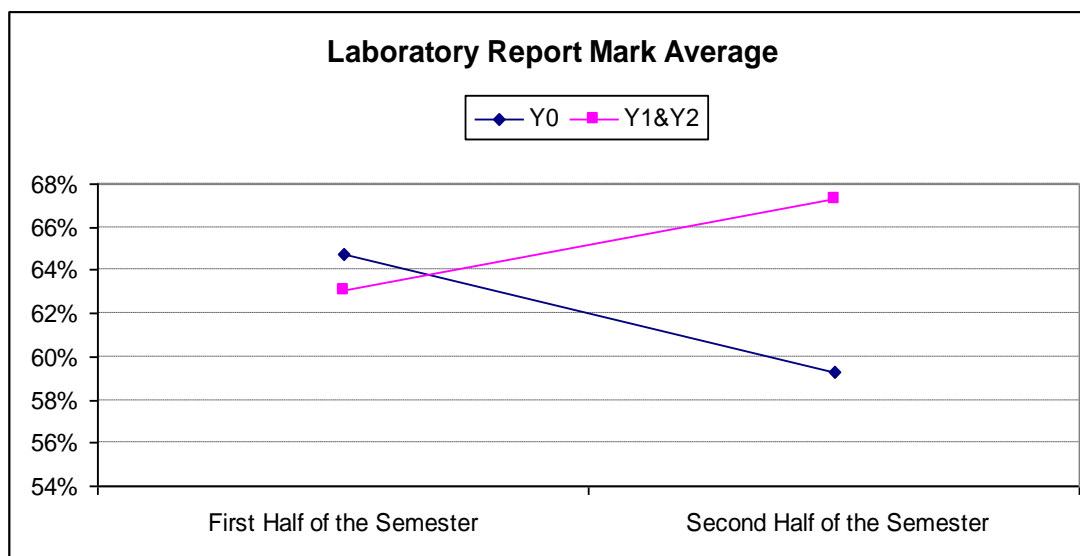


Figure 6.13. The laboratory report mark average of Y0 and Y1 & Y2 students as a function of the semester progress.

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.* Figure 6.13 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, $p\text{-value} = 0.430 > 0.05$). Table 6.11 provides a summary of all these statistics.

Table 6.11. 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

The analysis of the laboratory marks of the students revealed several conclusions. Firstly, *the students who have had better activation of the dimensions of Kolb's cycle (students of the experimental groups of Y1 & Y2) provided higher quality reports than their peers of the same year (students of the control groups of Y1 & Y2)*. Secondly, *the students who had better activation of the dimensions of Kolb's cycle 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. This adds to the evidence obtained via pre- and post-lab tests of better learning outcomes.

6.10 The Impact of Activating the Dimensions of Kolb's Cycle on the Marks of the Module Exam

As mentioned in Chapter 3, the lab supports the core content of the second year course, which is formed around the process control loop shown in Figure 4.3. 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 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.*

6.11 Survey of the Undergraduate Students Opinions of the Process Control Lab

A survey about the Process Control Lab was delivered to the students towards the end of the course in the 2007-2008 academic year. The survey, as shown in Appendix 3, aimed to investigate questions in relation to the process control lab such as:

- 1- The students' usage of the virtual lab: How long? When?
- 2- The students' preference for conducting the pre-lab preparation session: Virtual? Remote?
- 3- The students' opinion of the different components of the process control lab, e.g. the pre- and post-lab tests.
- 4- The impact of the remote experimentation in the lecture on motivating the students towards the hands-on lab session and on understanding the demonstrated theory.
- 5- The process control labs' impact on different factors of importance to the engineering curriculum goals, e.g. continuing an engineering career, team-working skills etc.

- 6- Whether there is any difference in the responses of the students who attended preparation session with the virtual lab and those who did not.

In total, 33 students responded to the survey. Twenty of them had not attended the preparation session, while 13 had attended. Reports of the findings are shown in the following subsections.

6.11.1 *The Students' Usage of the Virtual Lab and their Preference of Preparation Session Mode*

The students were asked whether they had downloaded and used the virtual lab, and if yes, for how long and whether before, after or before and after the hands-on lab session. The statistics show that 55% of the control group students (N = 20) vs. 61.5% of the experimental group students (N = 13) downloaded and used the virtual lab. The average usage of the control group is 46.1 minutes vs. 95 minutes for the experimental group. The experimental group's average usage is dominated by one student, who reported 300 minutes; the average of the rest is 54 minutes.

The Mann-Whitney U test returned a p-value = 0.758 for the software download and a p-value = 0.607 for the usage period, revealing no statistically significant

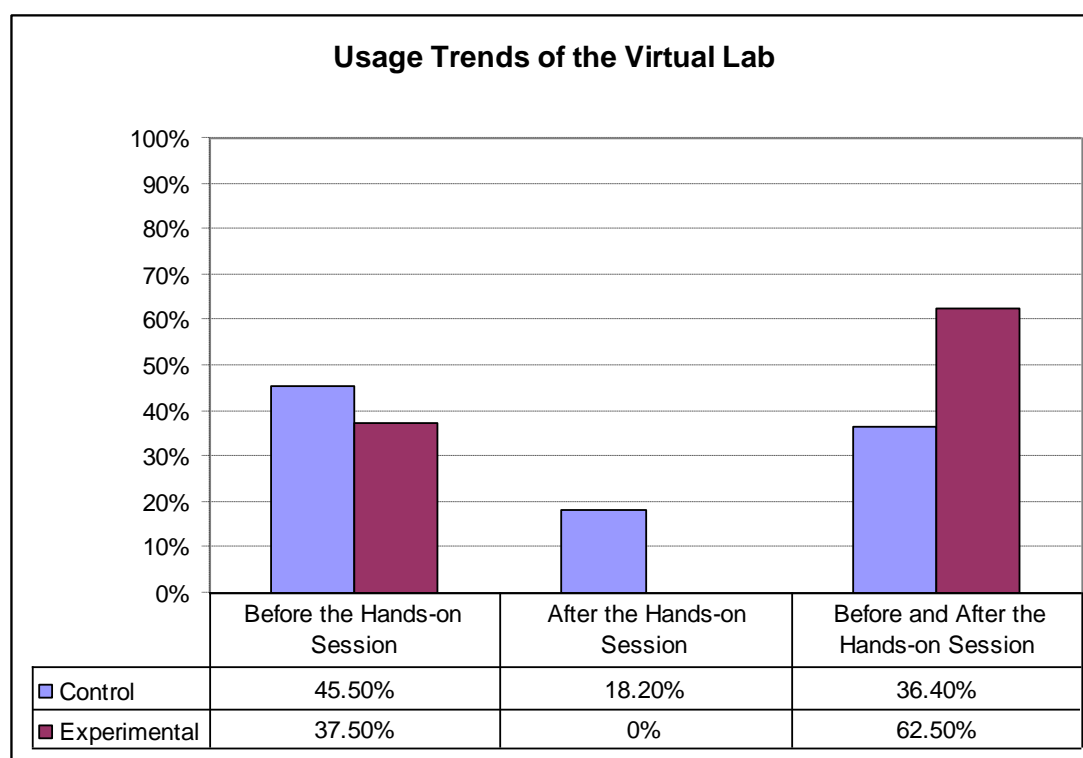


Figure 6.14. The trends of the virtual lab usage. The majority of the control group students used the virtual lab before the hands-on session, while the majority of the experimental group students used the virtual lab before and after the hands-on session.

difference between the control and the experimental group students. The statistics are summarised in Table 6.12. The control group students who used the virtual lab (N = 11) tended to do so before the hands-on session (45%), while the experimental group students (N = 8) tended to use the virtual lab before and after the hands-on session (62.5%). Figure 6.14 shows the details of the usage trend of both groups. The students' preference of conducting the pre-lab session is similar between the control and the experimental groups, with 53.8% of both groups preferring to use the virtual lab and 46.2% preferring to use the remote lab.

Table 6.12. Statistics of the virtual lab software download and usage.
Number of samples (control/experimental) is 13/20 for Q1 and 6/9 for Q2.

Question	Asymptotic Significance (the p-value) of the Mann-Whitney U test	Value% (Con./Exp.)
Q1. Software downloaded and used?	0.758	Yes (62.5/55)
Q2. Average usage (min)?	0.607	95/46.1

6.11.2 *Students' Opinions of the Newly Introduced Components of the Process Control Lab*

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. Question 7 of the students' survey (shown in Appendix 3) aimed to measure the students' opinion of the new components and to investigate whether there is a difference in the responses of the control and the experimental group students. The students 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 (Question 8).

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 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. Figure 6.15 shows the responses of both groups towards the usefulness of the virtual lab. 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.

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 contextualise 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. Figure 6.16 shows the responses of both groups to this question. 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 6.13.

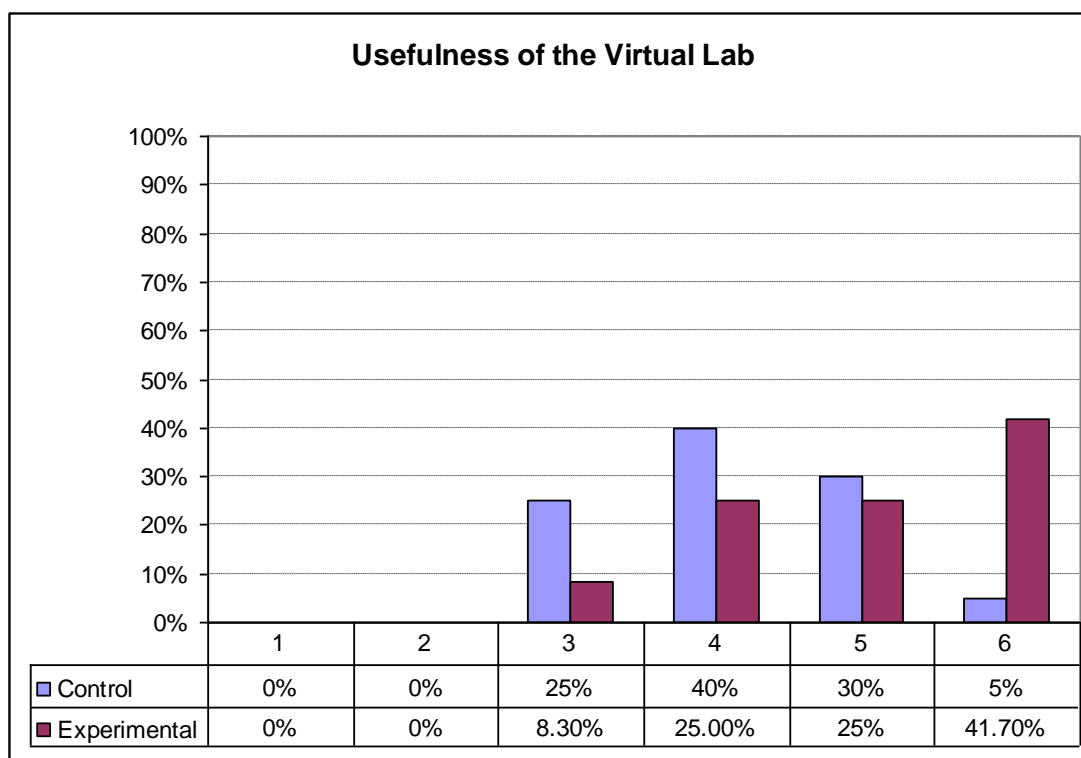


Figure 6.15. The perceived usefulness of the virtual lab by the students of the control and experimental groups: 1 = Not useful at all, 2 = Very little useful, 3 = A little useful, 4 = Probably useful, 5 = Quite useful and 6 = Very much useful.

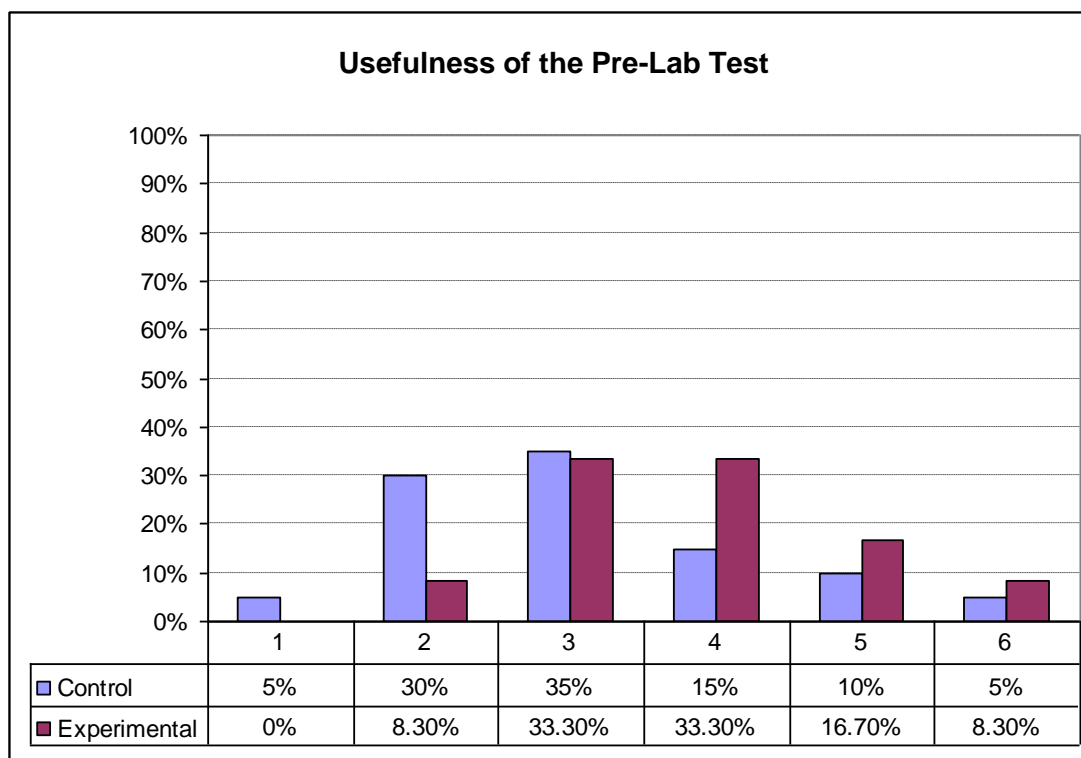


Figure 6.16. The perceived usefulness of the pre-lab test by the students of the control and experimental groups: 1 = Not useful at all, 2 = Very little useful, 3 = A little useful, 4 = Probably useful, 5 = Quite useful and 6 = Very much useful. Experimental group students were more positive towards the test than the control group students.

Table 6.13. 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

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 enhanced activation of the prehension dimension of Kolb's cycle has a statistically significant impact on motivating students towards further inquiry and experimentation, therefore providing a better constructivist experience for laboratory education.

6.11.3 *The Impact of the Process Control Lab on the Students*

The last question of the students' survey (Question 11 in Appendix 3) aimed to investigate the students' opinion of whether the process control lab was motivating in relation to six variables: 1- Continuing an engineering career; 2- Studying further control principles; 3- Application of theory into practice; 4- Instrumentation awareness; 5- Understanding the importance of process control principles. The students' response for each parameter was on a scale from 1 = Not at all, 2 = Very little, 3 = A little, 4 = Probably, 5 = Quite and 6 = Very much.

Generally, the students have responded positively for all six parameters with means of responses higher than four for every single parameter. The analysis has not shown statistically significant difference in the response of the students of the control and the experimental groups for any of the surveyed variables, nevertheless, the control group students have had a slightly more positive attitude. Figure 6.17 shows the distribution of the responses of all students and Table 6.14 shows the statistical significance analysis results.

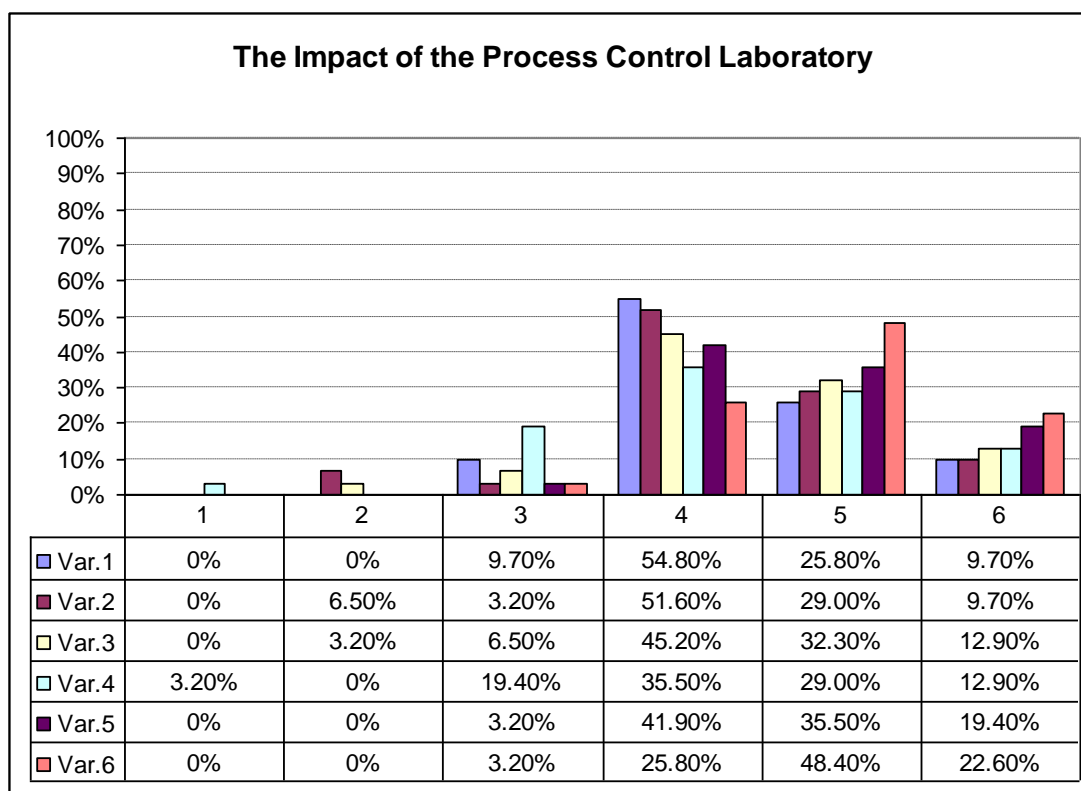


Figure 6.17. Answer distribution of the students (control and experimental together) on the process control impact: 1 = Not at all, 2 = Very little, 3 = A little, 4 = Probably, 5 = Quite, and 6 = Very much. Var.1 = Continuing an engineering career; Var.2 = Studying further control principles; Var.3 = Application of theory into practice; Var.4 = Teamwork skills; Var.5 = Instrumentation skills; Var.6 = Understanding the importance of process control principles.

**Table 6.14. The impact of the Process Control Lab on the students.
Number of samples (control/experimental) is 20/13.**

Variable	Exact Significance, Mann-Whitney U test (the p-value)	Means (Con./Exp.)
1- Continuing Engineering Career	0.244	4.50/4.09
2- Studying Further Control Principles	0.403	4.40/4.18
3- Application of Theory into Practice	0.611	4.50/4.36
4- Teamwork Skills	0.583	4.40/4.00
5- Instrumentation Awareness	0.427	4.80/4.55
6- Understanding the Importance of Control Principles	0.611	4.95/4.82

6.12 Survey of the MSc Students Opinions of the Process Control Lab

The PID control section (Week 2 session) of the Process Control Lab is a compulsory part of the MSc course 09CGP075 – Advanced Computational Methods for Modelling & Analysis of Chemical Engineering Systems, which was taught in February 2009. The three-hour session was conducted on the third day of the module, which is taught for one week, and a voluntary post-lab session (conducted with the virtual lab) was organised in the following week. The aim of the post-lab activity session is to offer an opportunity for cyclic learning, to measure how many students attended (e.g. motivation) and to measure the students' opinion of this activity. All students attended (N= 11) except one, who was unavailable due to an urgent family issue. After the module exam, the students were surveyed (see the questionnaire in Appendix 11). Nine students responded to the survey. Among the questions, students were asked to what extent the post-lab activity session was helpful in further understanding what has been learnt during the hands-on lab session, whether the post-lab activity should have been conducted with remote labs instead of virtual labs, how much they rated the importance of experience of the laboratory as a part of the module and whether they would like to have laboratories as core parts of other MSc modules that do not offer lab experience (see questions 5, 6, 7 and 8).

The students thought that the post-lab activity was very helpful in understanding further what they had applied and learnt in the hands-on session, as shown in Figure 6.18. None of the students had a negative opinion. This indicates the importance of cyclic learning and that the students would experience enhanced learning if the lab activity was repeated, even in another format.

Nevertheless, the students seemed to have a greater appreciation of the activity if it was conducted using the remote lab (see the presentation of Var.1 in Figure 6.19). Only one student (11.1%) indicated a preference for the virtual lab in the post-lab activity; the reminder of the students would significantly value a post-lab activity with a remote lab. It seems that the realism factor plays a role, a mode that students would like to select for further cyclic learning. The students prefer to work with something real rather than a virtual simulation.

As evidence of the students' appreciation of laboratory experience, all the surveyed students agreed or strongly agreed that the process control laboratory as is important as part of the taught module (Var.2 in Figure 6.19). Also, all the students think (mostly strongly agree) that other MSc courses that do not have

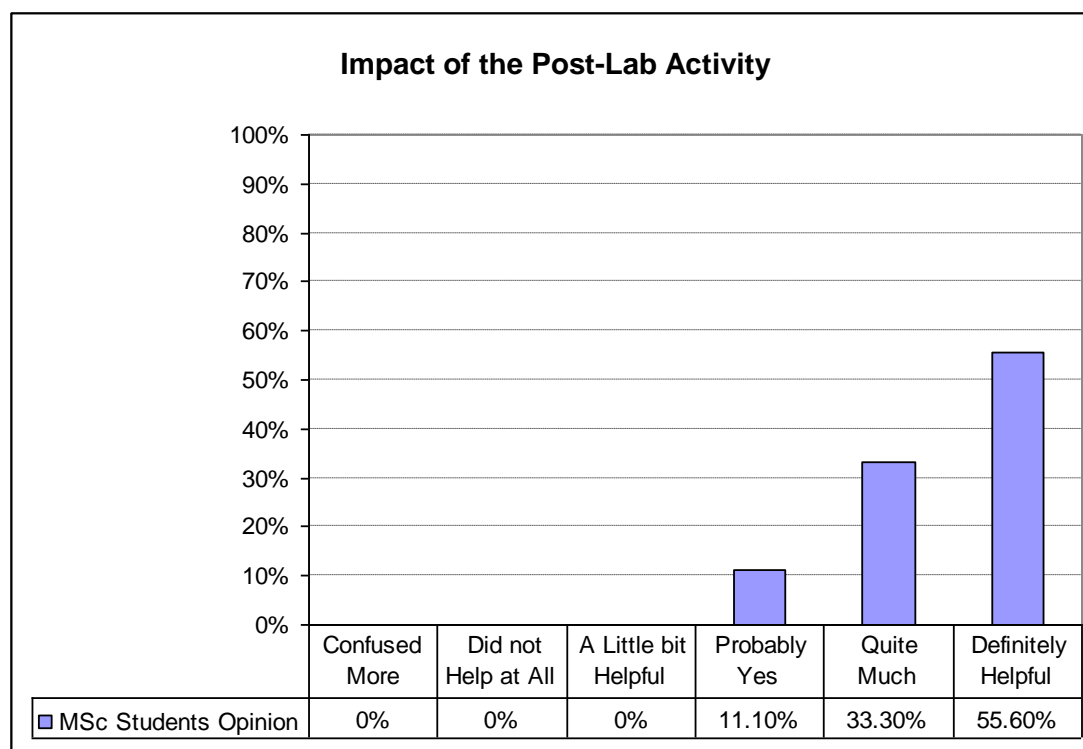


Figure 6.18. MSc students' response to evaluating the impact of a virtual lab-based post-lab activity. Students value significantly the experience, indicating the importance of facilitating events that activates cyclic learning.

labs should provide such experiential learning opportunities (see Var.3 in Figure 6.19).

As another indication of the importance of laboratory education in developing students' understanding and motivation, two supportive qualitative statements (out of five) were noted in question 9 of the MSc students' survey. The question aimed to inform the course lecturers of the students' opinion of the course through their ranking and their statement of why they chose that particular ranking. The course scored highly for two consecutive years; the mean was 1.64 (N = 11) for the 2008 batch and 1.71 (N =7) for the 2009 batch on a scale of 6, where 1 indicates the first rank (i.e. the best MSc module in the student's opinion). In their explanation of the ranking, one student wrote the following:

Student 1: *"The Module was rather too complex to be taught over one week. However, the control exercise would rank 1st because the experimental class gave us a complete better understanding of the subject."*

Student 2: *"The combination of practical and theoretical part made me interested in the subject and I had a lot of knowledge to implement in practice."*

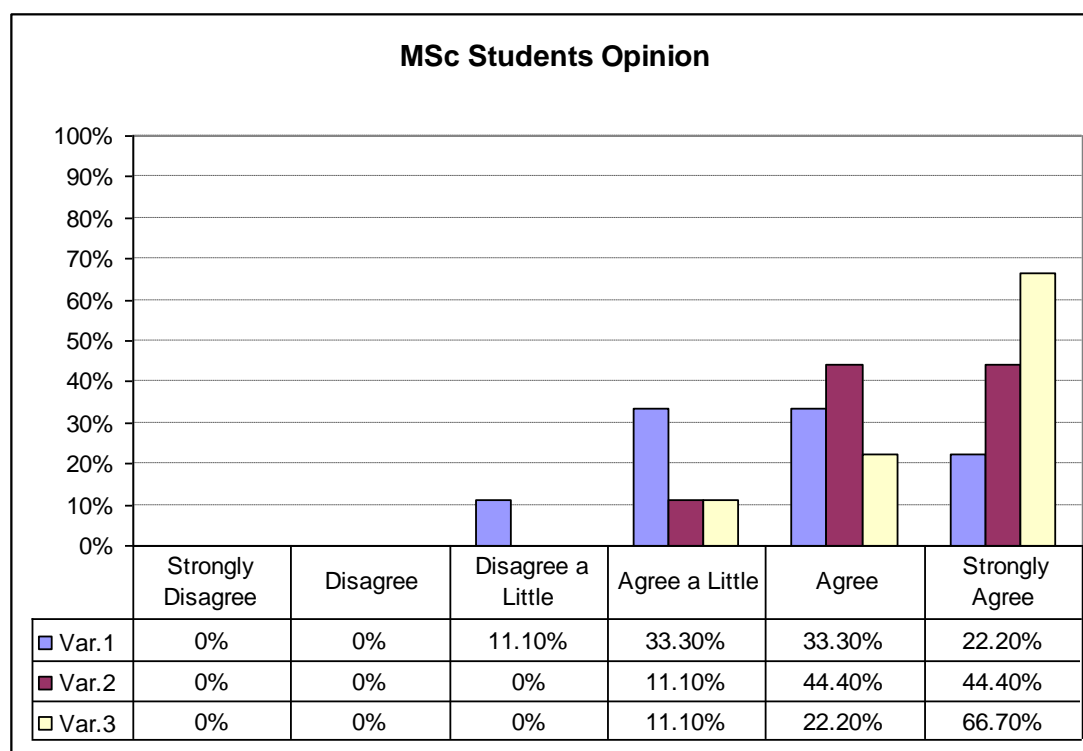


Figure 6.19. MSc students' opinion survey. Var.1 = Conducting post-lab activity with remote experiment; Var.2 = Importance of the process control lab as a part of the MSc module; Var.3 = Opinion of embedding laboratory experiments in other courses that do not offer labs.

The MSc students' survey provides evidence of the students' appreciation of laboratory work and its importance as a core part of the taught courses in postgraduate engineering curricula. The survey shows also that the students appreciate the opportunity of cyclic learning for digesting the hands-on lab session; nevertheless, they prefer having such an opportunity through a remote laboratory rather than a virtual lab mode, indicating the importance of the realism factor on students' acceptance of learning activities. This is in correlation with the constructivist pedagogy, which emphasises providing the students with authentic and experiential learning activities.

6.13 Summary of the Data Analysis and Findings of the Chapter

The analysis results of the second year course Instrumentation, Control and Industrial Practice shows strong consistency in the laboratory learning outcomes for the two academic years 2007-2008 and 2008-2009. *The students of the experimental groups outperformed, with a statistically significant indicator, the students of the control groups in the pre- and post-lab tests, in the quality of the*

laboratory reports and in the module exam. Statistical significance with higher means of the experimental groups has also been recorded in the students' appreciation of the pre- and post-lab tests, the virtual lab software and in the motivation towards further inquiry. Enhanced performance of the experimental group with regard to the mark for the lab report and final exam has also been observed. *These results provide evidence that the students who had better activation of the prehension dimension prior to the lab session have experienced more in-depth learning during the hands-on lab session.* In other words, *the transformation of knowledge through the lab experience into mental models (Kolb, 1984) has been more successful for students who worked on improving their prehension dimension.* This also indicates that a constructivist higher order learning in the hands-on lab session can be improved by more activation of the other stages of the Kolb's experiential learning cycle. A different behaviour was also observed during the laboratory sessions in the case of the experimental group students compared to the control group students. The former showed more interest in the hands-on lab session and insisted more on answering the pre- and post-lab tests compared to the control group students. *Groups were informed that the pre- and post-lab tests were voluntary and not included in the final marks for the lab or the course.*

A fair portion of the undergraduate students downloaded and used the virtual lab software. The students generally had a positive attitude towards the new components of the lab. However, less appreciation of the pre- and post-lab tests than the rest of the components was recorded. Post-lab tests were more favoured than pre-lab tests. The students think that the process control lab has impacted positively on their motivation towards continuing in an engineering career, studying further control principles, showing the application of theory into practice, instrumentation awareness and understanding the importance of process control principles.

The postgraduate students strongly considered the Process Control Lab (PID control section, Week 2 session) as an important part of the taught module. They strongly supported the idea of including more labs in MSc courses that do not contain hands-on experiential course work. They also highly rated the cyclic laboratory experience offered by a post-lab activity with a virtual lab. Nevertheless, they prefer such activities to be conducted with the physical rig remotely instead of a virtual simulation when possible.

6.14 Proposal of a Laboratory Education Model Based on the TriLab Concept and Kolb's Experiential Learning Theory

During the introductory lecture of the Instrumentation and Control module, students were introduced to the lab using a PowerPoint presentation and the lab was operated remotely in the classroom, with the aim of providing the realism feeling (telepresence) to students and stimulating them to conducting the lab experiments. This lecture structure is in correlation with the Concrete Experience stage of Kolb's cycle. At the end of the semester, in the module questionnaires, students were asked whether this had stimulated their interest in the lab sessions. A significant portion, 80.6%, of the students answered 'Yes'. One of the lectures was devoted to PID control. In this lecture, the theoretical background of the PID control approach was explained and the main features of the control algorithm illustrated by using the remote lab in the classroom. Again, a significant portion of the students, 78.1%, found this combination useful in understanding the theory more, providing evidence that the 'lab in the class' approach enhanced the Abstract Conceptualisation part of Kolb's cycle.

Well-designed pre-lab test questions or a preparatory session with the virtual laboratory helps students to reflect and contextualise the laboratory objectives, assisting in the realisation of the Concrete Experience stage. The use of the virtual lab and the design of reflective questions facilitate reflection, enhancing the Reflective Observation stage. Well-designed post-lab test questions give the students the chance to reflect on their experience in the lab session. These questions should be designed to help implement a meaningful model of the knowledge in their memory based on the lab session experience. This also helps to enhance the Reflective Observation stage. Embedding pre- and post-lab testing in the context of laboratory education urges the students to prepare well, which enhances the Active Conceptualisation stage.

According to Kolb, constructivist learning occurs in a cyclic spiral way, where a new cycle of learning builds upon a previous one (Kolb, 1984). Therefore, it is an important objective of engineering education, in particular laboratory education, to motivate students towards further higher levels of learning or experimentation.

Remotely operated labs offer the chance for flexible further investigation and experimentation, i.e. they offer the possibility of higher order learning. This additional activity may involve additional theory investigation (Abstract Conceptualisation), Active Experimentation and Reflective Observation. Remote labs offer the students a chance to repeat the experiment and have further

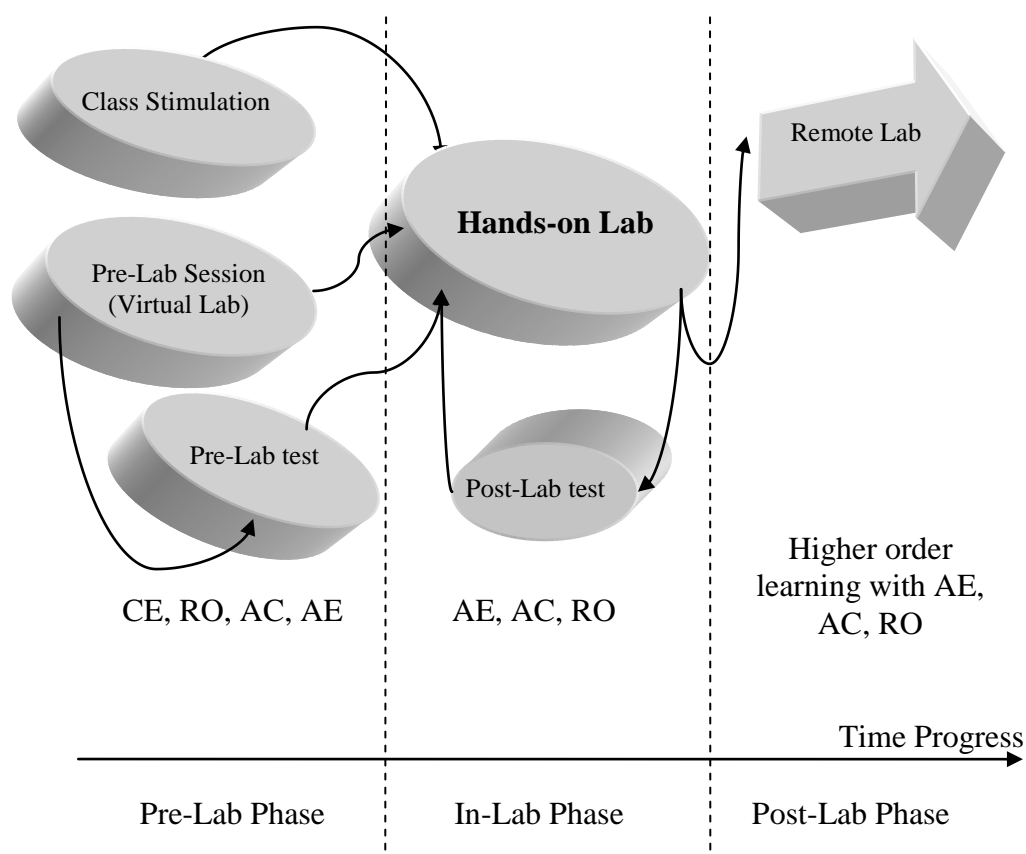


Figure 6.20. Abdulwahed-Nagy Laboratory Education Model, based on Kolb's theory. The extra activities facilitate higher order learning via activating the different stages of Kolb's cycle: Concrete Experience (CE), Reflective Observation (RO), Abstract Conceptualization (AC) and Active Experimentation (AE); See section 2.3.3.

reflection on their hands-on session (Reflective Observation). Both undergraduate and postgraduate students had a positive attitude towards conducting post-lab experimentation. The virtual lab also offers a similar opportunity; however, there is a fundamental difference between the virtual lab and the hands-on or remote lab, which is represented by the belief factor. Generally, the students favoured the hands-on experience or remote experience more than the virtual experience, providing evidence for the importance of remote experimentation that keeps the realism factor vs. the pure simulated lab.

In the laboratory session, students are mainly immersed in the Active Experimentation stage of Kolb's cycle. A poor outcome of laboratory education can be correlated with the poor balance of the other stages of Kolb's experiential learning cycle. Little attention is generally paid to laboratory activities that may lead to constructivist learning during the hands-on session. The results of the pedagogical experimentation shown throughout this chapter indicate that modifications can be introduced to the teaching methodology according to which

classical hands-on laboratories are taught. These modifications, with the aim to enhance constructivist learning, are suggested in the context of Kolb's experiential learning cycle and are implemented using recent advances in information and communication technologies, particularly in conjunction with the TriLab model that was proposed and developed in Chapter 5.

In classically taught laboratories, the AE is the main active stage. The absence of the other stages either during the lab session or prior to the lab session may explain the poor learning outcome during the laboratory sessions. This has led to the proposal of additional laboratory activities that would enhance the other learning stages in Kolb's cycle.

Table 6.15. Kolb's cycle mapping for laboratory education.

Activity	Mapping to Kolb's Cycle
Remote Experimentation in the Classroom	CE, AC
Pre-Lab Test	CE, RO, AC
Post-Lab Test	RO, AC
Hands-on Session	AE, AC, RO
Virtual Lab	RO, AC, AE
Post-Lab Remote Experimentation	RO, AC, AE, and Higher Order Learning

The mapping of the different elements of the laboratory education system to Kolb's cycle is proposed in Table 6.15, while Figure 6.20 shows a conceptual model of the constructivist laboratory based on Kolb's experiential learning cycle. The model is composed of three consecutive phases: 1) pre-lab, 2) in-lab and 3) post-lab. The pre-lab phase includes activities such as in-class stimulation and preparation session with a virtual lab and a pre-lab test. The in-lab phase includes the process of conducting the hands-on experiment followed by a post-lab test. The post-lab phase includes activities that activate further in-depth learning and inquiry, proposed to be conducted via a remote connection to the rig.

Academics who are interested in applying the model in a similar way to how it has been achieved in this project would need to implement virtual and remote access modes to the hands-on experiment (e.g. building a TriLab via LabVIEW

and Joomla). In the pre-lab phase, first they would introduce the students to the hands-on lab during a lecture by conducting a remote operation of the experiment. Next they would arrange a preparation session via the virtual lab component, and finally would conduct a 10-15 minutes pre-lab test. During the in-lab phase, student would conduct the hands-on experiment and have to conduct a 10-15 minutes pos-lab test. In the post-lab phase, students would have access to the rig remotely to conduct additional experimentation activities.

The three phase structure of the model (pre-, in- and post-lab) can be generalised to enhance the pedagogy of almost any engineering laboratory. Choosing the specific activities for every phase of the proposed model in a way that activates additional stages of Kolb's cycle (e.g. such as shown in Table 6.15) may vary depending on the nature of the lab, availability of resources and logistics.

The proposed pedagogical model, shown in Figure 20, has been called the Abdulwahed-Nagy Constructivist Laboratory Model and was well received at the FIE 2008 conference (Abdulwahed and Nagy, 2008). The session chair, who is the editor of the *IEEE Transaction on Education* journal, has invited the authors to submit an extended paper on the topic. However, the model and part of the findings of this chapter had already been submitted to another high-impact factor educational journal, *JEE*, (Abdulwahed and Nagy, 2009a).

6.15 Conclusions

In this chapter, the learning outcomes of the laboratory sessions are corroborated in the context of the well-known pedagogical theory, Kolb's experiential learning cycle. The following proposition has stated that the often reported poor learning outcome of the laboratory session is mainly due to weak activation of the prehension dimension of the learning cycle before coming to the lab. The pedagogical experiments based on combined application of pre- and post-lab tests and the three dimensional laboratory (application of the combination of hands-on, virtual and remote experiments) have provided statistical evidence of the proposition. In particular, introducing the virtual lab to the pre-lab preparation session has lead to considerable improvement in the students' conceptual understanding during the hands-on lab session. It has also lead to a reduction in the cognitive load of the students. Furthermore, it has lead to higher quality laboratory reports and improved marks in the final exam of the module. These results were consistent for the two academic years 2007-2008 and 2008-2009, indicating the robustness of the methodology and the used

instruments. The students' survey reflected positive opinions of the Process Control Lab. These results provide empirical support to Kolb's experiential learning theory and its proposal of the two axis nature of the learning process. The results demonstrate that designing engineering laboratory education based on a well-developed pedagogical theory can lead to better learning outcomes. Based on the pedagogical experiments, a novel model of laboratory education was introduced that has its pedagogical background in the experiential learning theory of Kolb. An algorithm of implementing Kolb's cycle utilising virtual and remote modes of the hands-on lab as well as by introducing additional lab activities has been proposed.

Chapter 7.

CLOSING THE DISTANCE; LABORATORY EXPERIMENTS IN THE CLASSROOM

Overview

This chapter introduces a new classroom practice, whereby theory lectures are supplemented with remote experimentation in the class. The remote component of the TriLab has enabled the application of this approach in undergraduate and postgraduate courses in the Chemical Engineering Department of Loughborough University. This has been accompanied by measurements of the impact on students' attitude and learning. After the introductory sections, the research questions and the methodologies are outlined. Then individual sections further detail the data analysis and findings. Overall, the approach has left a positive impact on several aspects of learning and the students are comfortable with the method. The findings are summarised and linked with pedagogical theories. The chapter ends with concluding remarks.

7.1 Introduction

Recent discussions of constructivist pedagogy emphasise the role of delivering education in more authentic and real contexts, urging a change in the classical classroom lecture model towards more active participation of the students (Herrington and Oliver, 2000). Since engineering is to large extent an applied science. Hence, it is important to be taught in its genuine context rather than in the dominant theory-oriented mode (Mills and Treagust, 2003). One important aspect is to support the theoretical classroom lectures with real applications. Laboratories are essentially provided in engineering education as a platform for showing the application of theory into practice. However, most labs are not portable and cannot be moved into the classroom to show the links between theory and practice in real time during the lecture. One solution to this problem is to close the distance through remote operation of the laboratory rig during the

lecture. This approach is also useful in enriching the number of utilised rigs through sharing experimental rigs among institutes. This chapter reports the approach of utilizing and sharing experiments remotely for classroom lectures. It also reports the students' opinion of this novel approach.

7.2 Why Use Labs in Classroom Teaching?

Classroom lectures are frequently reported to be boring and lacking in interactivity (Marsh, 1998). Many lecturers report a low attendance rate of students in the lectures (Shannon, 2006). Research has shown that the students' attention to the lecture may decrease severely after 10-18 minutes (Johnstone and Percival, 1976). In classical lectures, the students passively receive the information delivered by the lecturer. Too much delivered theory may frustrate engineering students, who have selected to study that field mainly because it is an applied science. Some lecturers are aware of this problem and try to incorporate authentic applications or experiments in their classroom lectures to support the theory explanation. An engineering demonstration kit in the classroom was used as early as 1964 (Kingma, 1964). Blending electrical and electronics engineering lectures with experimentation is generally easier than for other disciplines due to the small size and low cost of designing experimentation kits. Examples from engineering lectures can be found in Robbins and Fawcett (1973), Froehlich et al. (1978), Croskey (1990), Zain (1994) and Lewin (1999 & 2002). Many researchers have reported the positive impact of augmenting classroom theory with experimentation. A different way of combining theoretical lecture with experiments is to use the laboratory space for teaching instead of the typical classroom space (Vogit et al., 2003).

For many engineering courses, bringing the physical laboratory kit or rig into the classroom is simply impossible due to the size, weight, logistics or non-portability of the rig. Remote laboratories offer a unique chance to close the gap between pure theory lectures and the need to authentically illustrate the applicability of these theories to engineering students. Remote labs have been reported as a motivating and enjoyable experience (Aktan et al., 1996). This factor may contribute significantly to the efficiency of the engineering theory lectures.

7.3 Outline of the Research Questions in Association with Remote Experimentation in the Classroom

Remote experiments in the classroom have been used in MSc and undergraduate courses. Measurements of the impact have been taken during the MSc course CGP075 Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems in the years 2007, 2008 and 2009, and the undergraduate course CGB914 Instrumentation, Control and Industrial Practice during the 2007-2008 and the 2008-2009 academic years.

The measurements aimed to answer the following Research Questions (RQ):

- RQ1: What is the students' opinion of the impact of a blended (theory and experimentation) lecture vs. theory lectures? In particular, what is their opinion with regard to the following factors:
 - Enjoyment
 - Conceptual Understanding
 - Motivating role of the lecture towards an engineering career
 - Motivation towards studying more theory about the presented material
- RQ2: To what extent and why are the PID control experiments in the classroom helpful in understanding theory? What is the students' attitude towards exploiting remote experiments in the classroom with other courses?
- RQ3: Does the students' opinion of RQ1, RQ2 and RQ3 differ as a result of using different rigs?
- RQ4: What is the impact of a blended lecture on students' understanding in a quantitative measure?

RQ1, RQ2 and RQ3 were investigated with students of the MSc course, while RQ4 was investigated with students of the undergraduate course. The next section outlines the methodology used in investigating these research questions.

7.4 Outline of the Methodology of Measuring and Analysing the Impact of Remote Experiments in Classroom Lectures

Measuring RQ1, RQ2 and RQ3 was achieved via questionnaires, while measuring RQ4 was achieved quantitatively via the use of the Audience Response System

(ARS) and a developed set of multiple-choice questions about PID control theory. The ARS is a learning technology which enables the lecturer to quickly collect students' response in multiple-choice questions and display the results in a convenient way. An instrument containing several multiple choice-questions about PID control was developed and used in the classroom lecture in association with remote PID control experimentation. The responses to the instrument were collected using the ARS. Extended discussion of the ARS is presented in the following chapter.

Descriptive statistics are used to report the findings of the measurements of RQ1, RQ2, RQ3 and RQ4. RQ3 is investigated using the Mann-Whitney U hypothesis test and statistical significance measures. Further details of the methodology, measurements and analysis of the research questions are reported where appropriate in the following sections.

7.5 Remote Experimentation in a Postgraduate Course Classroom

RQ1, RQ2 and RQ3 were investigated for an MSc course. Two different experimental rigs were used: the Cambridge WebLab (Selmer et al., 2007) and the Loughborough iLough-Lab described in Chapter 5. The following subsections provide a description of the module outlines methodology, measurements and analysis of the research questions.

7.5.1 Outline of the Module

Experiments in the classroom were conducted with the MSc Module CGP075 Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems in the Chemical Engineering Department at Loughborough University in 2007, 2008 and 2009. The postgraduate module was organised as a part of the new MSc programme in Advanced Chemical Engineering with IT and Management, which started in 2007. The module aims to introduce the students to topics such as dynamic modelling, optimisation and PID control, which are applied to chemical processes, and to provide them with hands-on experience of the software tools used for implementing these techniques as well as relevant hands-on control laboratory experience. The lectures in the MSc classroom were delivered intensively within one week scheduled in February. The pilot experiment was done in 2007 as 15 minutes' remote experimentation during the PID lecture of the module. Following the pilot experiment, a dedicated remote

experimentation lecture for demonstrating PID control was assigned for the 2008 and the 2009 batch.

7.5.2 The Remote Experimental Rigs

Two different experimental rigs were used to explain the theory in the lecture: the Cambridge WebLab and the Loughborough process control lab. The rigs were used in classroom demonstrations to support the theoretical topics of control engineering, in particular demonstrating the PID control and tuning algorithms. This also aimed to show the students a real example of remote operation, which can be found in many industrial plants. After the students were introduced to PID control, a real application was demonstrated through the remote connection to the experimental rigs. In both cases, the experimental interface and the live web camera transmission were projected simultaneously to give the demonstration more realism.

The Cambridge WebLab was used in the modules taught in 2007 and 2008. The Cambridge WebLab is a non-ideal reactor designed for achieving a chemical reaction between phenolphthalein (PHEN) solution and sodium hydroxide solution. The solutions are kept in separate tanks and there is a third tank containing water. The flow rates from the tanks to the reactor are controlled via three PID control loops that regulate peristaltic pumps. When the reaction takes place, the solution in the reactor turns pink. The intensity of the colour reflects the PHENOH³-concentration. There is a fourth PID loop to control the intensity. For the 2009 course, the Loughborough Process Control Lab, which was introduced in Chapter 4, was used instead of the Cambridge WebLab. The Process Control Lab demonstrates PID control of a liquid level in a vessel, hence it differs in nature from the Cambridge WebLab but the principles of PID control remain the same.

7.5.3 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 was achieved and a demonstration of 15 minutes' 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.



Figure 7.1. Remote experiments during the postgraduate lectures (top: 2008 course - a student performing the remote control of the Cambridge WebLab; bottom: 2009 course - students looking at the results of the PID control of the remote experiments using the Loughborough Process Control Lab).

In 2008 and 2009 courses, the demonstration was conducted for 50 minutes. 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, PI or PID control structures are based on their real observations. The remote experience was stimulating for the students and the dynamics of the class changed remarkably after the remote experiments were introduced in both years. Figure 7.1 shows the remote experimentation in the MSc lectures of the 2008 and 2009 years.



Figure 7.2. The students' voting results of one of the multiple-choice questions during the experiential lecture of the 2009 MSc course.

In both years, the audience response system (ARS) was used (TurningPoint, 2008) to enhance the interactivity of the lecture. The students had to answer multiple-choice questions. Their answers are collected and presented through the ARS hardware and software. A quantitative representation shows up immediately after the students have answered, as shown in Figure 7.2. The voting system has been used in other lectures, too, during the module. Table 7.1 shows a summary of the usage of the remote experiments in the MSc classroom.

Table 7.1. 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



Figure 7.3. Using the iLough-Lab remote experiments in an undergraduate lecture. Remote connection to the Armfield rig with live video transmission was made to support theory with authentic experimentation.

7.6 Classroom Experiments in the Undergraduate Course

The remote lab has been used on several occasions in the second year classroom lectures for two purposes. The first purpose was to stimulate the students towards the subject and towards the compulsory laboratory sessions, as indicated in Chapter 6. The second purpose was to support lecture theory with real-time experimentation to clarify the theory and show its applicability in an authentic manner. Experiments in the classroom were also conducted in the first year course Process Balances to provide real-time and real-life illustrations of various dynamic behaviours of stable and unstable processes. Figure 7.3 shows an undergraduate lecture with classroom experimentation.

The video transmission has added important authentic value to the remote experimentation, as the students thought the results maybe generated by simulations before starting up the video transmission.

7.7 Answering the Research Questions in Relation to the Impact of Remote Experiments in the Classroom

This section provides details of measuring and analysing the research question RQ1, RQ2, RQ3 and RQ4 in relation to remote experimentation in the classroom.

7.7.1 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 (see Question 4 in Appendix 11). A conceptual model of the methodology of targeting RQ1 is shown in Figure 7.4.

Questionnaires were collected after the module oral exam; there were 11 respondents in total for 2008 and 9 respondents for 2009. The data were entered into SPSS to obtain descriptive statistics of the measurements. The statistical analysis of the students' responses for 2008 and 2009 are shown in Figure 7.5 and Figure 7.6. 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.

4. How would you rate the combination of teaching theory and real experimentation in the classroom (remote lab lecture combined with the previously PID control theoretical lecture) in comparison with the purely theoretical lectures that were taught along your MSc program?

1= Much less 2= less 3= The same 4= More 5=Much more

- | | | | | | |
|---|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| a. The enjoyment factor. | 1 <input type="checkbox"/> | 2 <input type="checkbox"/> | 3 <input type="checkbox"/> | 4 <input type="checkbox"/> | 5 <input type="checkbox"/> |
| b. The conceptual understanding | 1 <input type="checkbox"/> | 2 <input type="checkbox"/> | 3 <input type="checkbox"/> | 4 <input type="checkbox"/> | 5 <input type="checkbox"/> |
| c. The motivating role towards engineering career. | 1 <input type="checkbox"/> | 2 <input type="checkbox"/> | 3 <input type="checkbox"/> | 4 <input type="checkbox"/> | 5 <input type="checkbox"/> |
| d. Studying more theory about the presented material. | 1 <input type="checkbox"/> | 2 <input type="checkbox"/> | 3 <input type="checkbox"/> | 4 <input type="checkbox"/> | 5 <input type="checkbox"/> |

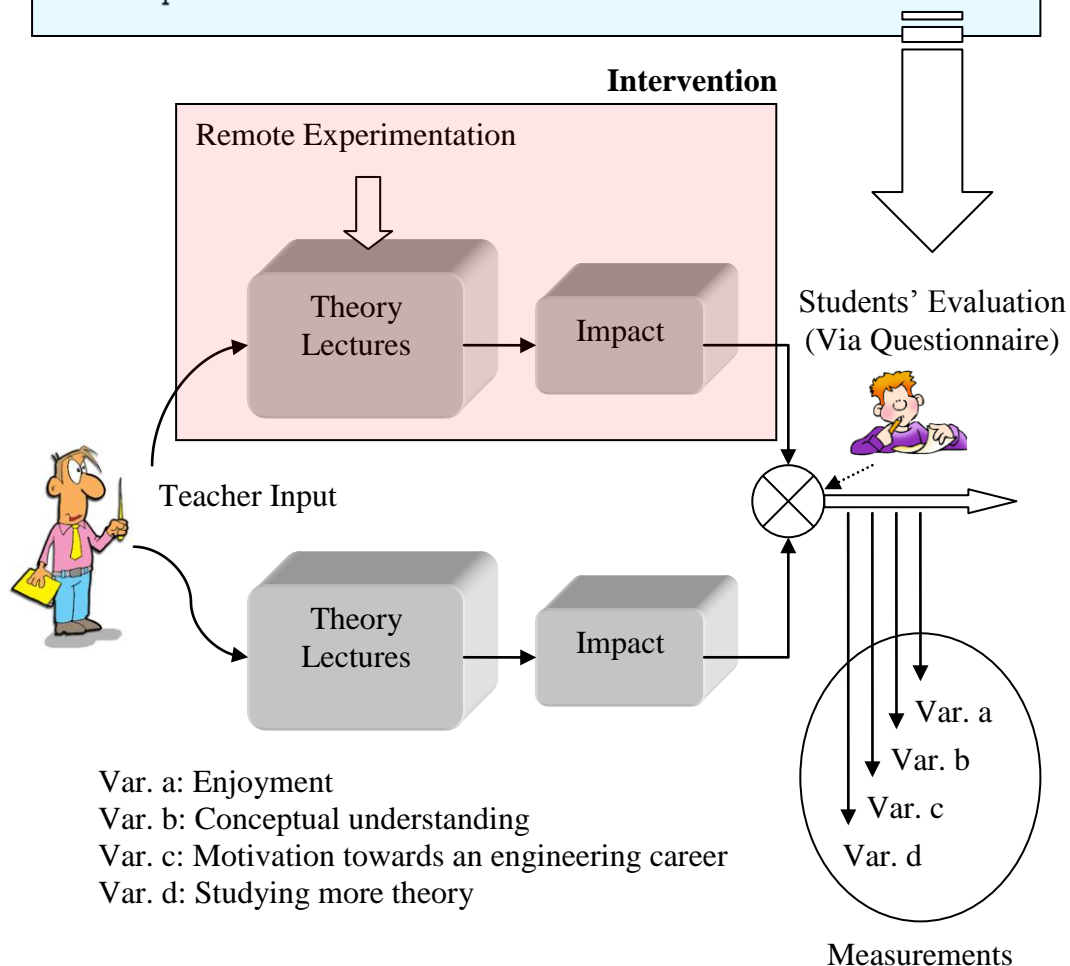


Figure 7.4. Methodology of measuring the impact of the blended lecture with experimentation approach vs. classical lectures on students.

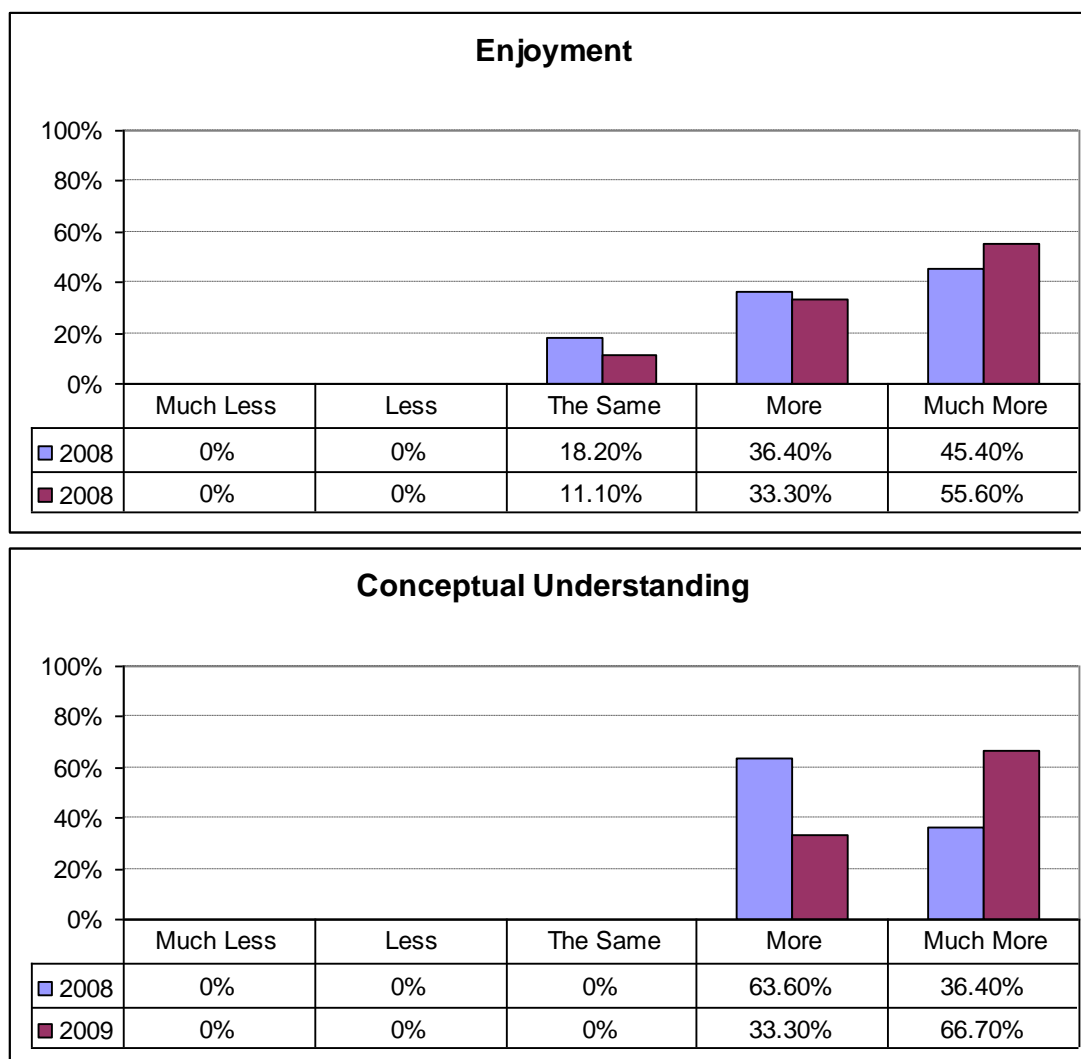


Figure 7.5. Statistics of the students' response of the impact of the blended lecture with experimentation approach vs. the classical lecture on enjoyment and conceptual understanding.

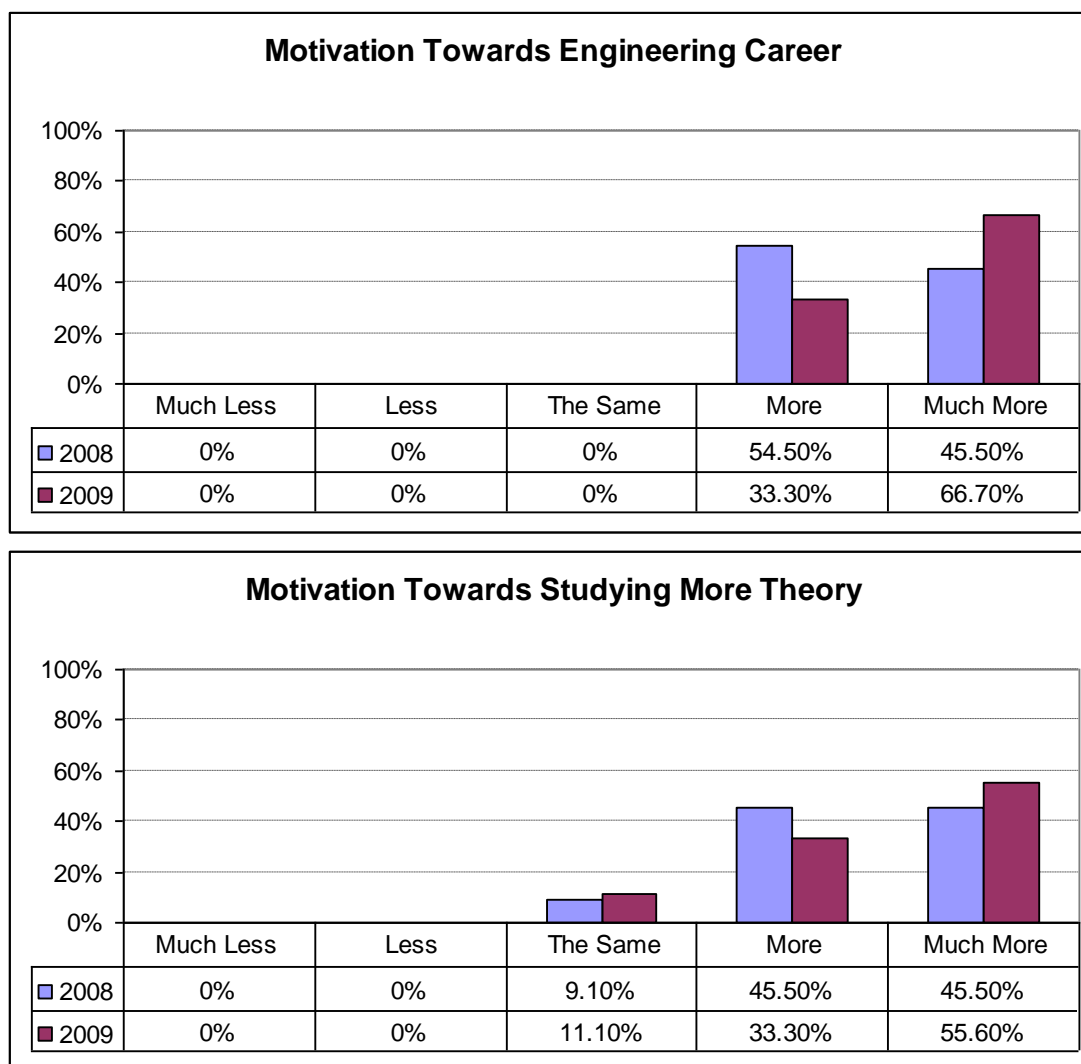


Figure 7.6. Statistics of the students' response of the impact of the blended lecture with experimentation approach vs. the classical lecture on motivation towards an engineering career and studying more theory.

7.7.2 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 (see Question 3 in Appendix 10). The findings are reported by means of descriptive statistics and the qualitative responses of the

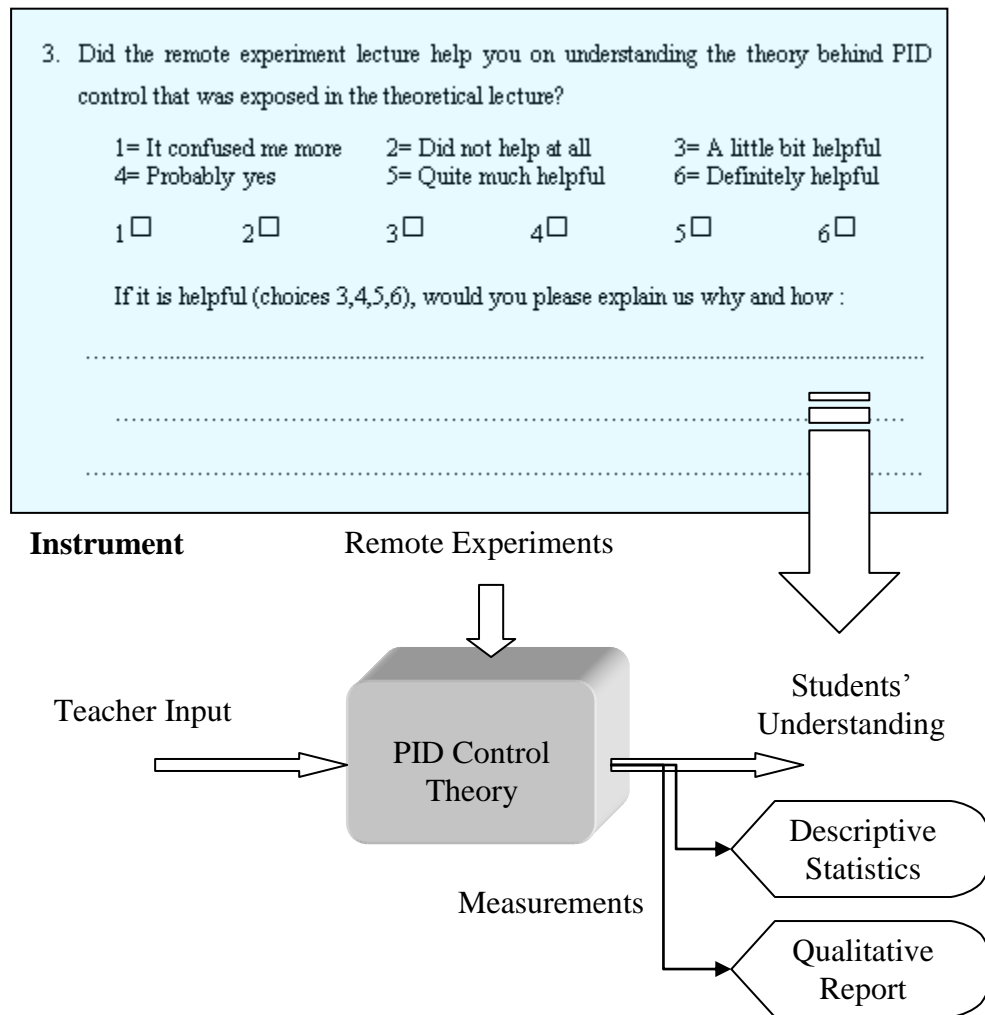


Figure 7.7. Methodology of measuring the impact of remote experimentation in the lecture on understanding PID control theory.

students. The methodology is shown in Figure 7.7, and the descriptive statistics of both years' surveys are shown in Figure 7.8.

The results show the positive opinion of the students. They believe that the remote 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.

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 practice."*

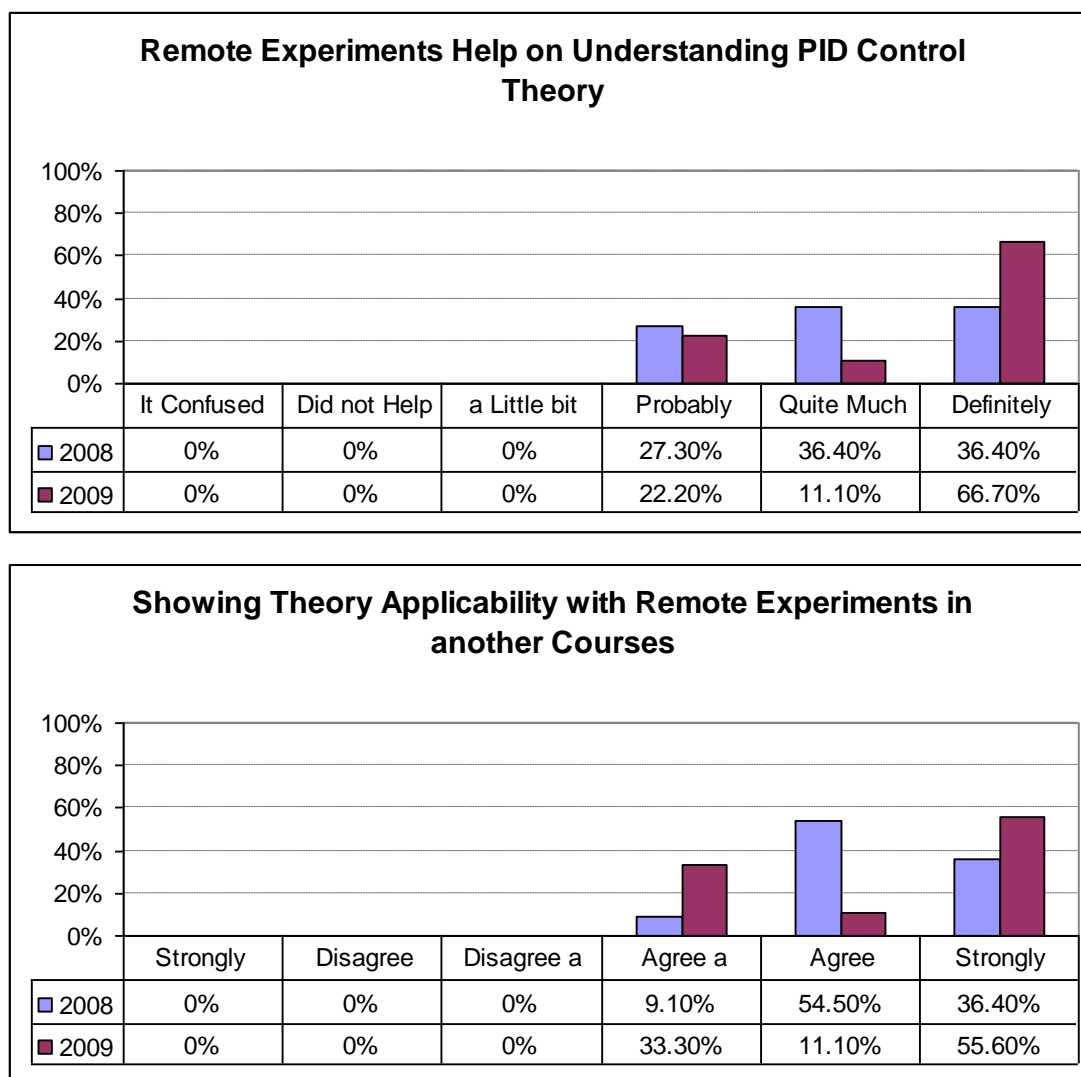


Figure 7.8. Statistics of the students' response about the impact of PID control experiments in the classroom on PID theory understanding and their opinion of embedding classroom experiments in other courses.

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 practice and to play with various K_c , T_d and T_i 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 (see Question 2 in Appendix 10). All students from 2008 and 2009 showed rather strong agreement with exploiting remote experiments in other courses to demonstrate the taught theory, and none reported disagreement (see Figure 7.8).

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.

7.7.3 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 was exploited remotely in one lecture in 2008, while the Loughborough Process Control Lab 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 one hour. To find whether there is a statistically significant difference between the two years’ surveys, the Mann-Whitney U test was used. Figure 7.9 shows the methodology of investigating this research question. The Mann-Whitney U test was achieved via SPSS. 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 7.2.

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).

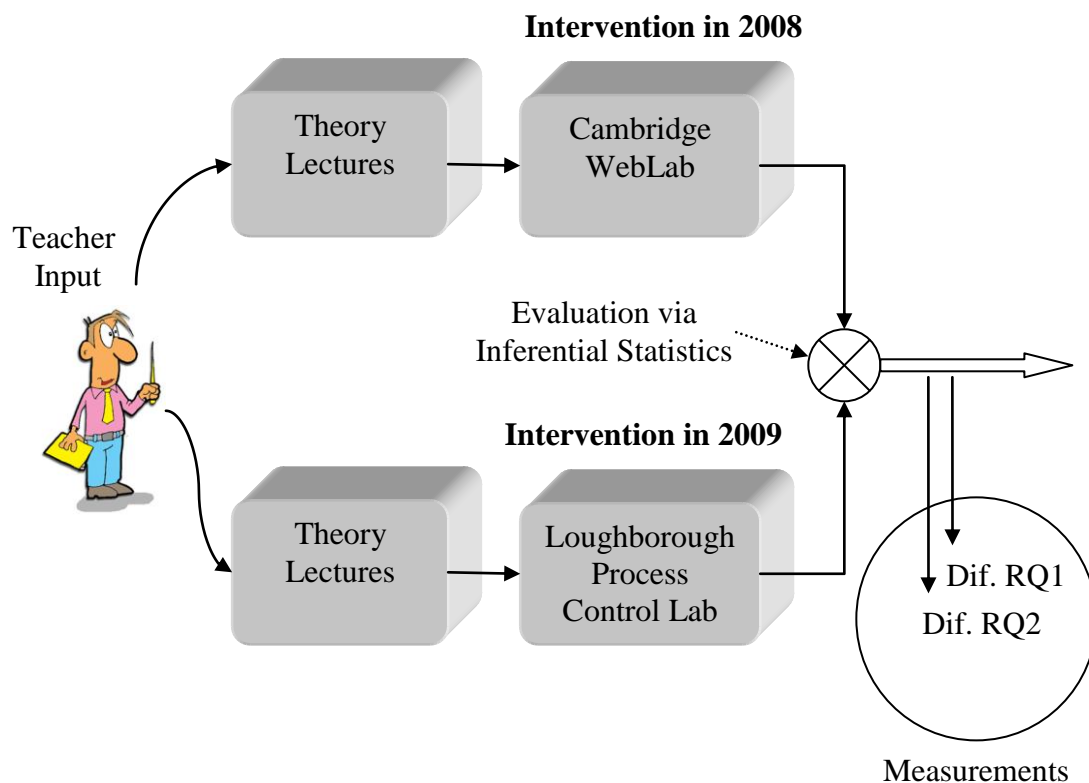


Figure 7.9. Methodology of measuring the difference in impact when using different experimental rigs in the classroom.

Table 7.2. 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 ¹
RQ3.2	0.261	4.36/4.67 ¹
RQ3.3	0.456	4.45/4.67 ¹
RQ3.4	0.766	4.36/4.44 ¹
RQ3.5	0.395	5.27/5.25 ²
RQ3.6	0.370	5.09/5.44 ²
RQ3.7	0.941	5.27/5.22 ²

¹Scale from 1 to 5 where 5 is the highest preference. ² Scale from 1 to 6 where 6 is the highest preference.

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

7.7.4 RQ4: Quantitative Measure of the Impact of Remote Experiments in the Classroom on Students' Understanding

This research question aimed to obtain a quantitative indication of the impact of remote experiments in the classroom on students' prehension of theory. The investigation was conducted with the second year chemical engineering students in the academic year 2008-2009. The experiment aimed to measure information retention after a pure PID theory lecture and after an interactive lecture that involved real experimentation in the classroom. The students took a quick assessment quiz using the voting system (TurningPoint, 2009) two days after the theory lecture. The quiz consisted of seven multiple-choice questions in relation with PID control and took 15 minutes to complete. One question was conceptual asking about the control loop arrangement. Three questions involved the theoretical calculation of PID, PI and PD controllers and three questions involved the qualitative judgement of different controllers, P, PI, PD and PID. Each question had seven to nine choices of answer with a single correct option. The last choice for each question is 'I don't know'. Two days after the quiz, an interactive PID lecture was conducted using the remote experimentation of the iLough-Lab. In this lecture, a qualitative explanation of PID control illustrated with real examples was performed. After 21 days, a second quiz was conducted. The seven questions were different but were carried out in the same sequence and followed the same concepts as the first quiz. Due to time limits, this quiz had only ten minutes to complete. The methodology of targeting this research question is shown in Figure 7.10. The 'Instrument' in the figure shows a sample of the used multiple choice questions. The full set of questions of Quiz 1 can be found in Appendix 14. The students performed better in the second quiz. The average correct answer was higher for four questions, equal for one question, and less for one question. The average mean of the second quiz was 35%, while the average mean of the first quiz was 29.66%. The individual means of the questions are shown in Figure 7.11. Students' engagement with the quiz has also improved. Engagement is measured by the choice 'I don't know'. The fewer 'I don't know' choices made, the greater the engagement, i.e. students are more willing more to think about the question and even take the risk of choosing an answer. The second quiz mean was 5.83%, while the first was 8.66%, indicating that students were motivated much more after the experience with the remote lab to think about and try to answer the quiz questions.

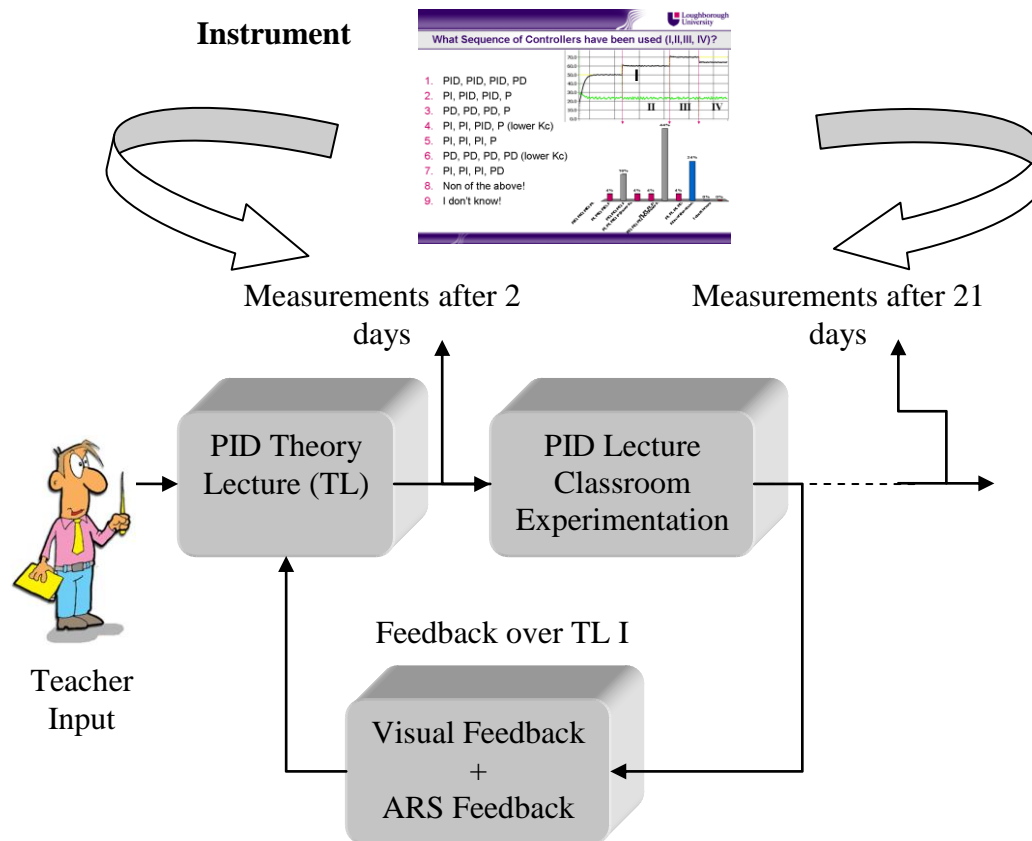


Figure 7.10. A conceptual model of the methodology of measuring the impact of classroom experimentation on the students' learning outcome in the undergraduate course.

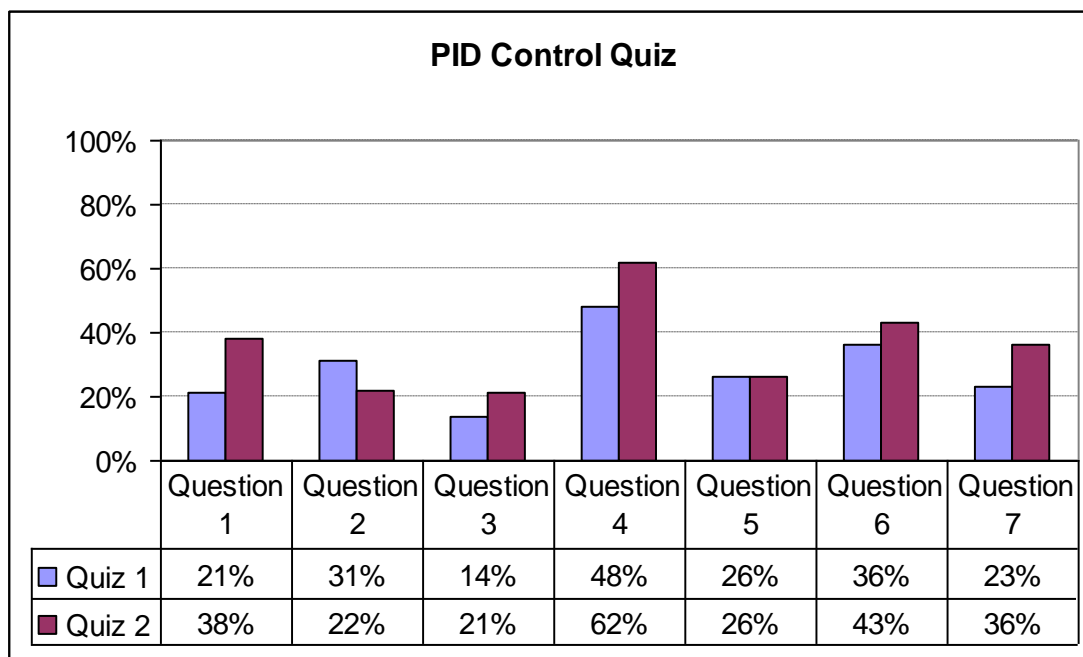


Figure 7.11. Individual means of the questions from the quizzes before and after the remote lab lecture for the 2008-2009 academic year. The experimental group students scored higher than the control group students in the majority of the questions.

The means of the post-lecture measurement in both cases (learning outcomes and the will to answer) are significantly higher; however, due to a corruption in the data file of the ARS software, conducting a statistical significance test was not possible.

7.7.5 Discussion of the Findings of Using Remote Experiments in the Classroom

Some difficulties in teaching control systems engineering are due 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 and 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 located in the AC/AE quadrante of Kolb's learning cycle shown in Figure 2.2, i.e. their learning style is a mix of abstraction (AC) and experimentation (AE) (Kolb, 1984). This finding has been reported by many other engineering education researchers (David et al., 2002; Stice, 1987). Hence, a pure theory lecture is not consistent with engineering students' learning style. The VARK learning style model suggests that learning styles are Read/Write, Visual, Aural and Kinaesthetic. 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. The learning pyramid model (Weenk, 1999) suggests that learning retention rates are different depending on the learning method (5% lecture, 10% reading, 20% audio/visual, 30%

demonstration, 50% discussion group, 75% practice by doing, 90% teaching others). This may explain the enhanced information retention obtained using the interactive lecture.

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 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. Part of the presented results in this chapter was demonstrated at the Global Colloquia on Engineering Education GCEE2009 conference (Abdulwahed and Nagy, 2009c).

7.8 Conclusions

Developing a remote version of a currently available hands-on lab incur a relatively lower cost compared to the initial cost of a hands-on lab. Yet, remote labs offer the advantage of sharing experiments among institutions and enriching engineering education. Remote labs open the door for new pedagogies such as classroom theory augmented with a real-time presentation of its applicability in an authentic experiment. The remote operation of the Cambridge WebLab and the Loughborough Process Control Lab has been used in postgraduate teaching in the classroom. The approach approved had a positive impact on the students during the lecture; however, it has limited the time available to devote to theory. The streamed video of the test rig played an essential role in validating the authenticity of the experiment. Remote experimentation has been applied in undergraduate courses and the results have shown improved learning outcomes. Such a positive impact may be related to the fact that augmenting lectures with real experimentation leads to enhanced cognitive perception.

Chapter 8.

PEDAGOGY; A CONTROL SYSTEMS ENGINEERING VIEWPOINT

Overview:

In this chapter, a control systems engineering view of pedagogy is presented. Quantitative dynamical models of learning are developed, namely open- and closed-loop learning. The modelling process was inspired by the tank level experiment, which was introduced in Chapter 4. A new model of forgetting, based on an engineering concepts is introduced. The models are analysed and their implications are described. The models are then used as the basis of describing two modes of lecturing: open- and closed-loop. A technology for closing the loop in the lectures is introduced with empirical findings of the students' attitude towards it. Empirical findings in the educational literature that support the predictions of the closed-loop models are provided. A discussion about considering the constructivist laboratory model that was introduced in Chapter 6 as a closed-loop learning enabler is provided. Finally, a section on proposing the 'Systems Pedagogy' concept as a field for engineering the education is provided and is followed by concluding remarks.

8.1 Introduction

Control systems engineering methods have been used in non-traditional disciplines such as biology (Wolkenhauer et al., 2005; Assmus et al., 2006), economics (Kendrick, 2005), finance (Sarychev, 2008), policy (Kim, 2004), management (Bond, 2008), software engineering (Litoiu et al., 2005), Internet engineering (Lu et al., 2006), physics (Sun et al., 2006) and psychology (Hollands and Wickens, 1999). The methods are much less used for quantitative and analytical analysis in pedagogy (Abdulwahed et al., 2009). This could be related to educationalists' reluctance and scepticism of using mathematical models to describe pedagogical processes (Yeung, 2006).

Feedback is the core of control systems engineering; feedback and regulation are rooted phenomena in nature and in science. Feedback and regulation can be found in biological living systems, galaxies and in quantum physical scales. For

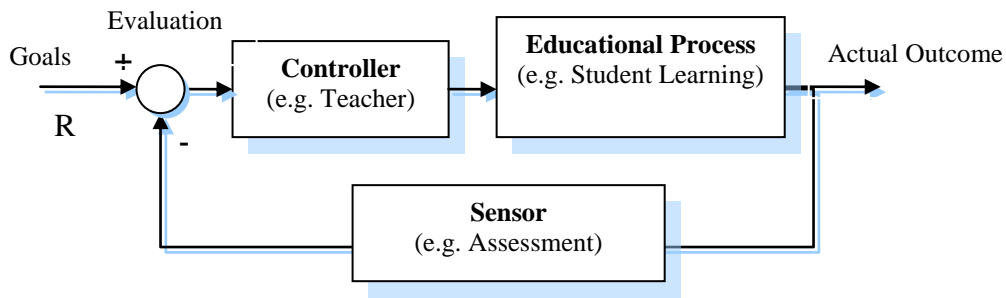


Figure 8.1. Feedback control system representation of a learning process. The controller can be the teacher, the process can be the student's learning and the sensor represents the assessment of actual learning outcomes. Evaluation of the discrepancy between the learning outcomes and actual learning is fed to the controller to act accordingly to reduce the gap.

instance, a countless number of feedback control loops are embedded in the human body (e.g. pressure and temperature regulation) and in our daily habits (e.g. car driving). Without such loops, any living system would collapse.

Many essential principles of control systems engineering can be applied to educational systems. In control systems engineering, measurements are taken through sensors. The more accurate the sensors are and the more frequently the measurements are taken, the better control of the system is achieved. Delayed measurement in control systems are known to destabilise the system. When no measurement is taken, or the feedback channel is broken, the closed-loop system turns into an open-loop system. This implies taking frequently accurate assessments and evaluations to guarantee stability and goal achievement of the educational processes. Educational processes that only evaluate once, e.g. a final exam, are open-loop systems. A comprehensive review of the correlation between pedagogy and control systems is provided in Chapter 2. The literature review of educational research shows a conceptual interrelationship between control systems and pedagogy in three main fields: *i*) feedback and formative assessment research; *ii*) self-regulated learning; and *iii*) instructional design.

In this chapter, it is proposed that pedagogical processes can also be modelled using a control systems engineering approach. Let's recall the feedback control loop of the process control laboratory shown in Figure 4.3. The loop is essential to establish a stable level control system. In a similar way, an educational feedback control systems loop can be represented as shown in Figure 8.1. The system to be controlled in this case is an educational process, e.g. students' learning, project-based learning progress etc. The controller can be the teacher or the student. Feedback is implemented through measurement sensors, e.g. assessment. The evaluation is the process of comparing the measured system

outcome with the system goals, e.g. a negative feedback loop. The goals are similar to the setpoint concept. The controller receives the evaluation result (the discrepancy) and acts accordingly to bring the actual outcome of the process into line with the process goals.

8.2 Why Develop Control Systems Models of Learning?

Many higher education lecturers are unaware of the importance of educational feedback and formative assessment during the learning process. This can be explained by the fact that, in general, many people poorly understand dynamical systems, even those with simple feedback loops (Jensen and Brehmer, 2003; Sterman, 2006; Senge, 2006; Moxnes, 2000; Sterman, 1989). Hence, computer simulations can provide an instrument to assist educationalists to realise the importance of feedback in the learning process. Simon (1982) argues that mapping of qualitative or conceptual models of socio-psychological theories into analytical quantitative models probably enhances the original theories. Explaining a descriptive theory in mathematical models could strengthen or degrade claims that are unverified through empirical studies, by using analytical evidence. Mathematical models are more precise than descriptive or conceptual models. Furthermore, using control theory methods for modelling socio-psychological behaviour could lead to a proposal of control techniques for effectively steering the process outcomes towards the intended objectives, e.g. an engineering approach.

The developed models in this chapter describe, in a conceptual but mathematical way, the learning process dynamics under two different modes of teaching/learning; open- and closed-loop (e.g. without or with feedback). They also allow computer simulations of the learning process given a specific didactic mode. The simulations, however, are not point-to-point exact progress of the learner knowledge construction level. Rather, they rather show predictions of the dynamics of each mode. These particular analysis tools are absent in instructional design research. In the next sections, a case of developing mathematical models of the two modes of learning using control systems engineering is presented.

8.3 Modelling Open- and Closed-Loop Learning

Most pedagogical models are conceptual or static. However, learning in principle is a dynamic process. Dynamical models are superior because they show the transition of state over time and allow future predictions of the state.

Furthermore, dynamical models enable access to control techniques, which can significantly improve the process behaviour. In this section, an investigation of modelling learning with control systems methods is discussed.

Teaching and learning methods can be implemented in a spectrum of ways which span over an axis of two extremes. One extreme is the open-loop teacher-centred approach (classical), while the opposite extreme is a closed-loop or student-centred approach (modern/constructivist).

The teacher-centred approach to learning is basically a passive transmitter (teacher) – receiver (student) model. Knowledge delivery in this model takes place in the form of narration, e.g. a lecture. The main assumption under this mode of teaching and learning is that the learners will be able to assimilate the transmitted information completely in their minds simply because they received it through their senses. Such an approach without any assessment and any involvement of the students in constructing knowledge is an open-loop process.

On the other hand, reflection, assessment and feedback are important characteristics of constructivist learning (Kolb, 1984). Knowledge construction is mainly the students' responsibility (Kolb, 1984; Caine and Caine, 1991; Tynjälä, 1999; Richardson, 2003; Piaget, 1978; Brown et al., 1989; Steffe and Gale, 1995). Constructivist learning can be either a self-regulated learning (SRL) process or student-centred with teacher guidance and effective feedback. Constructivist learning conforms to closed loop processes.

8.3.1 Modelling Open-Loop Learning

The perception of learning as a simple accumulation process based on teacher transmission (e.g. open-loop learning) was dominant in the pedagogical literature until two decades ago (Nicol and Macfarlane-Dick, 2006). Since learning is a process of accumulating knowledge, modelling can be made analogously with an engineering accumulating process, for instance electrical capacity charging or tank filling. Let's use the tank filling process, shown in Figure 8.2, as an example to demonstrate the model derivation.

The tank is filled through a pump that transfers the liquid from a source, e.g. water pipes. The input to the tank is the flow rate out of the pump; this flow rate accumulates the liquid in the tank and causes the liquid level to rise. The varying liquid level is the system output and the quantity is dependent on two main factors: the input flow rate and the tank itself, e.g. its dimensions and shape etc. For cylindrical tanks, the relationship between the input and the output is given as follows:

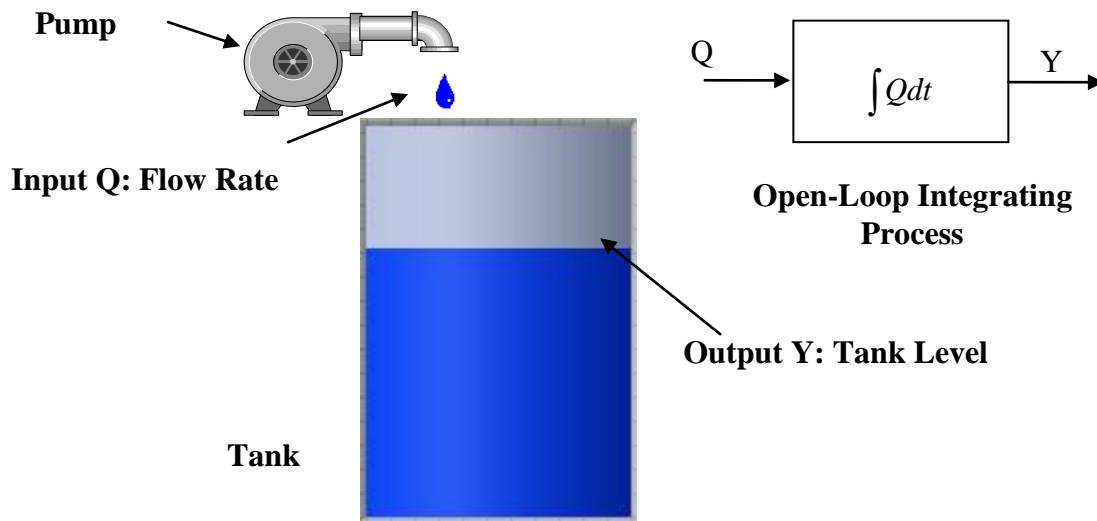


Figure 8.2. Tank filling system with an open-loop control systems representation.

$$\frac{dY}{dt} = \frac{1}{A} Q \quad (8.1)$$

where Y is the liquid level in the tank, A is the tank's cross-sectional area and Q is the input flow rate to the tank. Determining the level in the tank as a function of time and the input flow rate can be done by integrating the two sides of (8.1), hence the tank level can be written as follows:

$$Y = \frac{1}{A} \int Q dt \quad (8.2)$$

In a similar way, the classical teaching and learning approach is a process where the teacher (the pump) delivers information (during a lecture, for instance) with a specific rate (input flow rate). This information is assumed to accumulate in the students' mind (tank). Generally, the teacher will design the teaching unit and the information delivery rate in an assumed way that will reach a specific level by the end. However, in the classical approach there is no such feedback, e.g. assessment and evaluation that indicates what level has been accomplished (what information has been successfully learnt). The analogy between the open-loop filling tank system and the classical teaching and learning approach is shown in Figure 8.3. In a similar way to equation (8.1), one can write the model specifying the relationship between the teacher input and the transmitted information in the classical approach as follows:

$$\frac{dx}{dt} = au \quad (8.3)$$

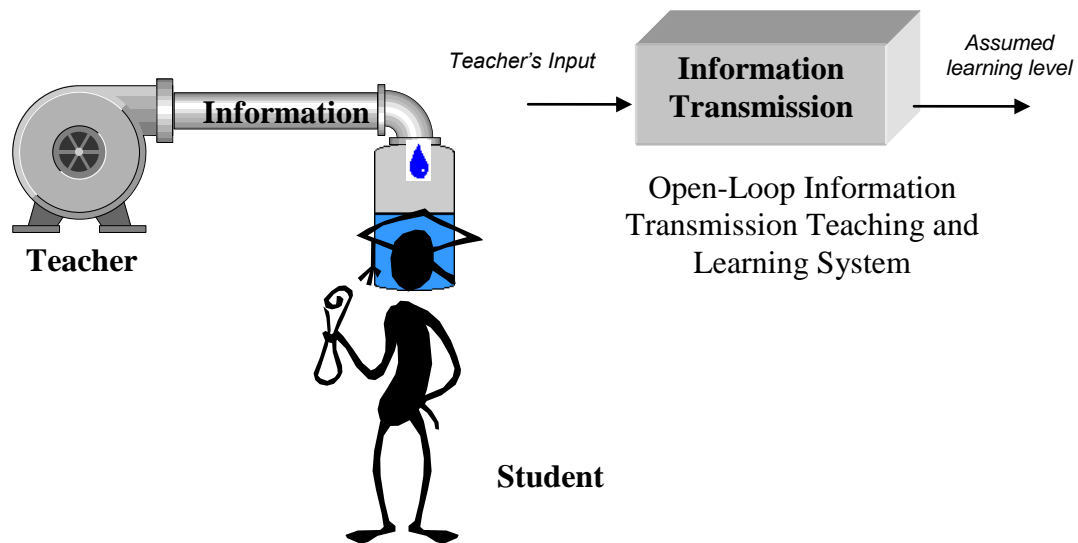


Figure 8.3. Engineering metaphor of open loop information transmission.

where x represents the accumulated knowledge, u is the teacher's input that determines the speed of information transmission (in other words, the teaching speed) and a is a variable that differs from one learning task to another and from one student to another. In the general simple case, this factor is considered constant, such as the case of the tank area in equation (8.1). This constant represents the students' presumed average capability to learn. The variable x represents the assumed integrated knowledge in the students' mind as being identical to those delivered by the teacher without any loss or decay. In this model, what is really described is 'Knowledge Transmission' but not necessarily the actual 'Learning'. From this model it is evident that the main controller of the learning process is the teacher.

8.3.2 Modelling Closed-Loop Learning

Closed-loop learning here is considered as a constructivist student-centred approach that involves the learners actively in the learning process and is distinguished with effective feedback and reflection practices. Mathematically speaking, the integrator (or the knowledge constructor) in this case will be the learner. Once the learner is given specific and clear learning objectives set by the instructor (or set by him/herself), he/she will work on constructing mental models that build-up the required learning objectives.

The learner will be fed back with information about the constructed mental models (internal or external feedback) after they are assessed. Hence, the learner will have an estimation of the gap between what has been actually learnt and

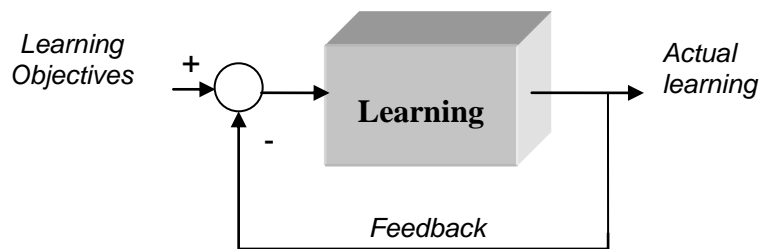


Figure 8.4. Closed loop learning model.

what should be learnt. This information about the gap constitutes the learning input to the learner. The learner continues the construction process until the actual learning level is identical to the set of learning objectives. Figure 8.4 shows a conceptual model of closed-loop learning. The process can be mathematically modelled as follows:

$$\frac{dx}{dt} = -a'x + r \quad (8.4)$$

where x is an internal state representing the actual learning level (already constructed knowledge), r is the learning objective (goal) and a' is the learning constant that may differ from one learner to another. In the analogy of a filling tank system, the pump in this case is mainly the student. The teacher, however, plays a coordinating role by setting the learning objectives, the learning resources (e.g. the source from which the pump will transfer the liquid) and assists in assessing the learner and giving feedback about the gap between what has been learnt and the learning objectives. In this case, the learner plays a greater role in controlling the learning process. The highest level of closed-loop learning takes place as a SRL mode. In this way, the learner takes full responsibility of setting goals, finding resources, determining suitable strategies, self-monitoring progress and self-evaluation.

8.4 Analysing the Open-Loop Learning Model

In this section, an analysis of open-loop learning is presented by means of simulations. A comparison of the approach is shown when the teacher delivers information to students of varied learning capability.

8.4.1 The Impact of the Difference in Students' Learning Capability

Let's assume that the actual learning ability (accumulating knowledge or achieving progress) in the passive learning mode for a student is about 50% weaker than the presumed average of the class, i.e. the constant a is less by 50%.

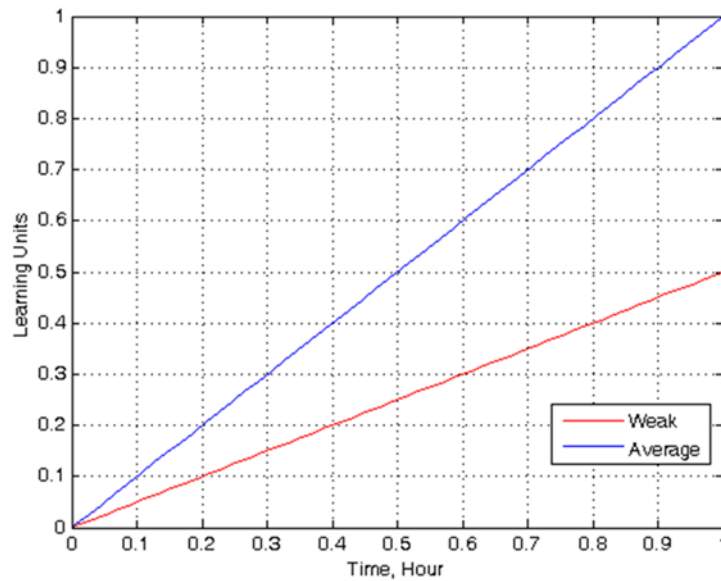


Figure 8.5. Simulation of a low capability student's achievement (red) vs. an average student's (blue) achievement in an open-loop learning mode.

In this case, there will be 50% less progress in the knowledge transmission process. Simulations of the model (8.3) for the average and the weak students are shown in Figure 8.5. The teacher will adjust the information transmission process input (e.g. the teaching rate) so that it delivers a learning unit during a specified time (let's say one hour as, as in lectures) according to the average students' capability of information retention that he or she expects. However, a weaker student with half the capability of the average will hold only half of the delivered information, shown in red in Figure 8.5. Since the teacher has no means of assessing the transmitted information to the weak student, the information delivery rate will probably not be re-adjusted (the variable u in equation (8.3)) to adapt to the weak students' needs.

8.4.2 The Impact of the Forgetting Factor on Information Retention

The review of cognitivism in Chapter 2 introduced memory functionality and the presence of the forgetting factor in humans. Let's consider the simplest exponential forgetting model of Ebbinghaus (1913), which is given by the following:

$$m(t) = c e^{-bt} \quad (8.5)$$

where m is the remembered information over time, b is the saving rate and c is the amount of the remembered information at the initial time. The factor b is affected by many factors such as the complexity of the taught material, the stress,

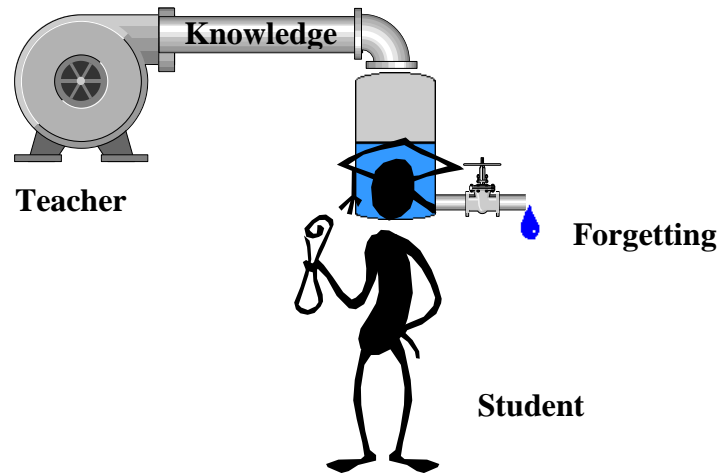


Figure 8.6. Engineering perception of open-loop knowledge transmission.

lack of sleep and the relationship of the learnt material with previously stored information in the long-term memory etc.

In the case of open-loop learning, where information is received once (e.g. during a lecture) and not reviewed, the actually retained information in the learner's mind is strongly affected by the forgetting factor. Hence, the forgetting curve described in (8.5) should be integrated with the solution of the open-loop differential equation to result in the actually retained information y :

$$y = x e^{-bt} \quad (8.6)$$

In this section, another way of modelling the forgetting factor is proposed. Here, the forgetting factor is represented in a similar way to an output leak in a tank through an output valve, as shown in Figure 8.6.

The system dynamics explaining the water level in the tank can be given as follows:

$$\frac{dY}{dt} = \frac{1}{A} \times (Q_{in} - Q_{out}) \quad (8.7)$$

where Q_{in} is the inflow rate and Q_{out} is the outflow rate, given by:

$$Q_{out} = K \sqrt{Y} \quad (8.8)$$

where K is a constant dependent on the nature of the output valve.

Hence, the open loop learning model which includes the forgetting factor effect as an output leak that can be written as follows:

$$\frac{dx}{dt} = a(u - f), \quad f = k \sqrt{x} \quad (8.9)$$

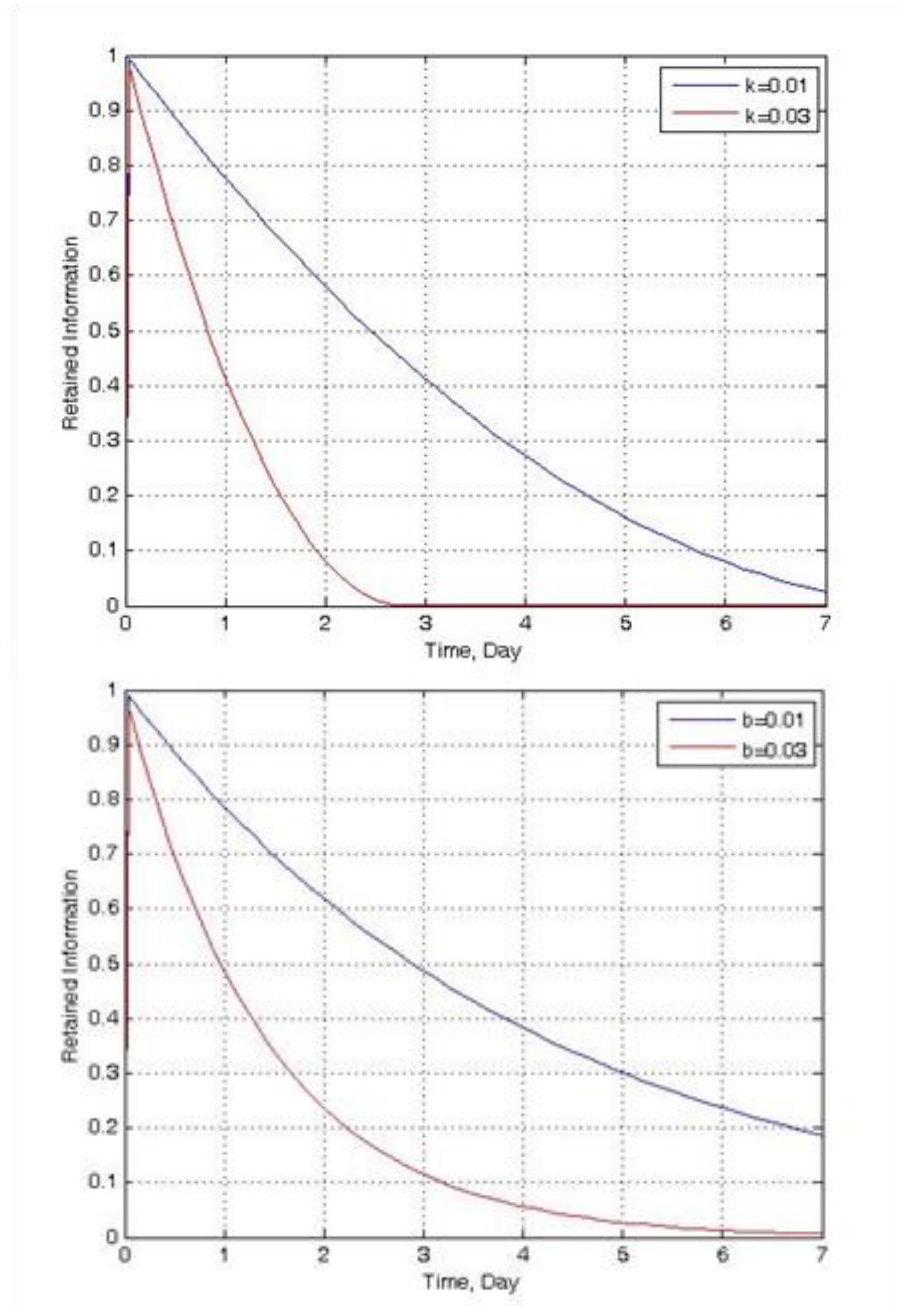


Figure 8.7. The impact of the forgetting factor on information retention. Engineering model (top) and cognitive psychology model (bottom). The curves simulate the forgetting phenomena for different values of the forgetting factor.

where u is the control input (a teacher variable related to the information delivery speed) and the forgetting factor is represented by f , which is a function of the retained information. Simulations of the open-loop learning models in (8.6) and (8.9) are shown in Figure 8.7.

The simulations show the decay in retained information over a period of seven days after 1 hour of teaching. The blue and red curves represent different values

of the parameters k and b accordingly. The values are arbitrarily chosen for the solely purpose of simulation, hence quantitative conclusions cannot be obtained. However, qualitative and conceptual evaluations can be performed. The simulation of the engineering model of the forgetting phenomena as described in (8.9) shows similar behaviour to the exponential decay of equation (8.6). Hence, viewing the forgetting phenomena as a leaking process can be equally logical as viewing it as a decaying process.

The simulations in Figure 8.7 show the significant negative impact of the forgetting factor on retaining information in the open-loop learning process. Without rehearsal, most information will be lost over time.

Analysis of the closed-loop learning process is presented in the next section which shows the process dynamics of different capabilities of the students as well as the impact of the forgetting factor.

8.5 Analysing the Closed-Loop Learning Model

In this section, an analysis of closed-loop learning is presented by means of simulations. The closed feedback loop shown in Figure 8.4 and modelled by (8.4) holds two main advantages compared to the open-loop model:

- The closed-loop learning model of an accumulating process is an asymptotically stable system (Goodwin et al., 2001). This means that the learner will reach the defined set of learning objectives when constructing knowledge. This also implies that if the system deviates from its target, it will correct itself to get back to the desired objectives due to the feedback loop.
- The closed-loop model is robust, which means that the model uncertainty can be overcome by the feedback loop. The robustness implication is that the gap between low-achieving and normal students can be reduced by closing the loop. In other words, closed-loop learning is convergent compared to open-loop learning.
- Furthermore, the effect of the forgetting factor can be limited or neglected in the case of closed-loop learning compared to open-loop learning.

These characteristics are detailed in the following subsections.

8.5.1 The Impact of Differences in Students' Learning Capability

Let's assume that the actual learning ability (ability of accumulating knowledge or achieving progress) for one student is about 50% weaker than the presumed average of the class, i.e. the constant α' in equation (8.4) is less by 50%. The simulations in Figure 8.8 show that the 50% weaker student (red) will lag less than 10% behind the average students (blue) by the end of the assigned learning time (one unit). If more time is allowed, the weaker student will finally reach the asymptotic stable point similar to the average students (e.g. by allowing extra time space). This is different to the open-loop learning model where the weaker student will lack significantly behind the average class, as shown in Figure 8.5.

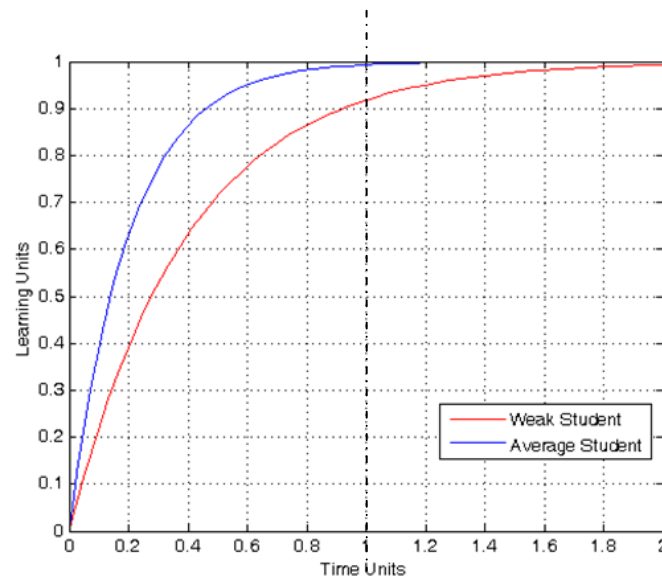


Figure 8.8. Simulation of a low-capability student's achievement (red) vs. an average student's (blue) achievement in a closed-loop learning mode.

8.5.2 The Impact of the Forgetting Factor

In the closed-loop learning model, the learners are immersed continuously in the knowledge construction process over longer periods of time. The process is accompanied by frequent assessment, reflection and feedback practices. This may significantly reduce the negative impact of the forgetting factor on information retention, or may even lead to a negligible effect, because information is being continuously rehearsed and transferred from the short-term memory to the long-term memory.

The new information builds upon previously stored information in the long-term memory and is linked with it. Whenever the learner receives feedback (self, peer, computer-based or teacher-based etc.) that some knowledge is missing, e.g. forgotten, he/she can work on retrieving it again. It is believed that frequent

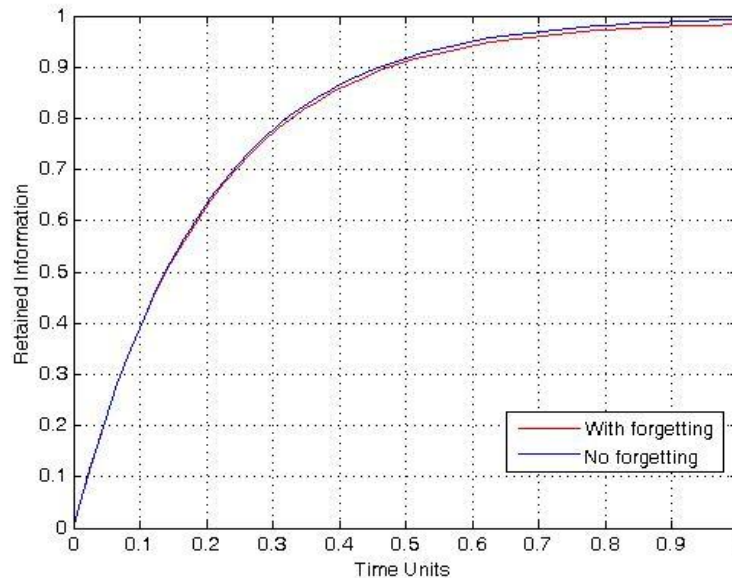


Figure 8.9. Closed-loop learning with the forgetting factor (red) and without the forgetting factor (blue). The forgetting factor value $b = 0.03$ was used for an exponential decaying forgetting model, as given by equation (8.6).

triggering of the stored information in the long-term memory over a long period of time may result in the information being stored forever (Slavin, 2005). The simulation in Figure 8.9 shows the negligible effect of the forgetting factor in case of feedback (red curve) compared with feedback with no forgetting (blue curve). The forgetting factor value used in this simulation is the same for the red curve in the bottom graph in Figure 8.7, i.e. $b=0.03$.

The open- and closed-loop learning models can describe many educational processes, such as project-based learning (Abdulwahed et al., 2009), the lecturing and learning of a module (Abdulwahed et al., 2008b) and conceptual pedagogical models such as self regulated-learning, or Kolb's experiential learning cycle (Abdulwahed et al., 2008c). In this chapter, only details of applying the open- and closed-loop learning models to describe the lecturing process are provided.

8.6 The Lecturing Process

In this section, an expansion of the previous open- and closed-loop learning models is applied to the lecturing process.

8.6.1 Modelling and Simulation of Open-Loop Lecturing

Traditional lecturing models have generally adopted an open-loop mode, in which the teacher conducts a lecture, lasting approximately an hour, in which

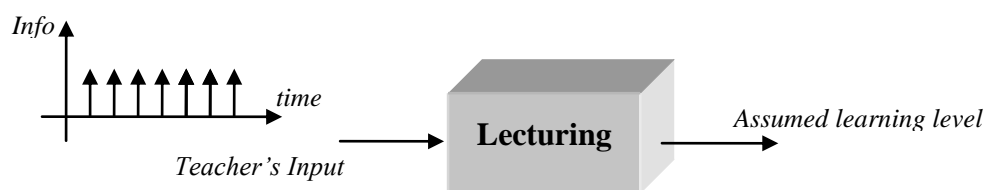


Figure 8.10. Open loop lecturing is modelled as a process with teacher input and an output representing the student's learning level.

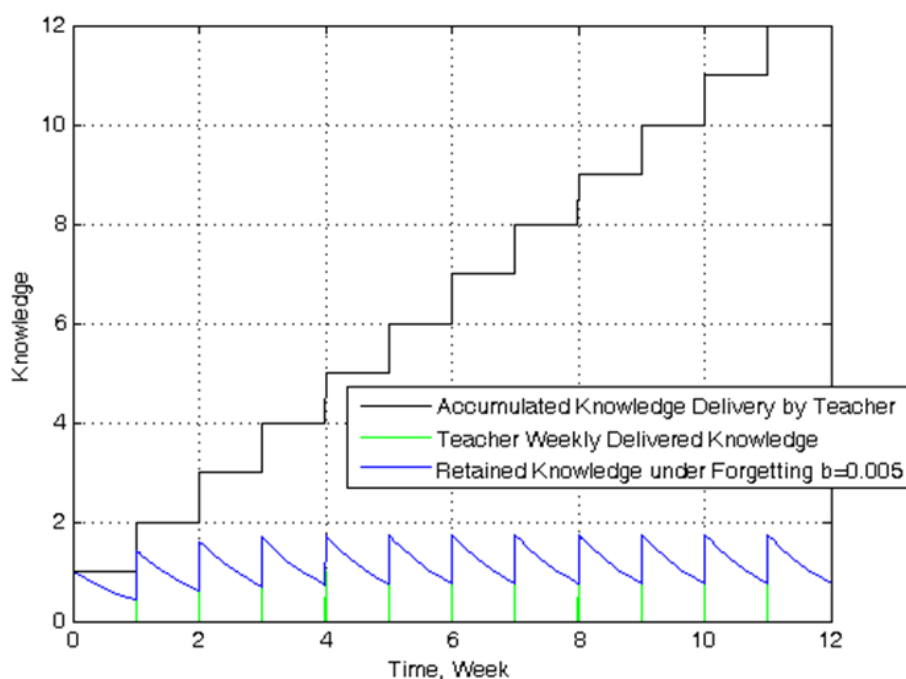


Figure 8.11. Open-loop lecturing. The delivered accumulated information (black), teacher input (green) and of the actually retained information with the presence of the forgetting factor (blue).

material is presented to the students. Feedback is seldom practised in the classroom (Hattie and Timperley, 2007). Feedback practice during the lecture (in any form) is significantly more likely for teachers who received teaching training compared to those who did not; however, providing elaborated feedback about a task (FT) is low in both cases (Bond et al., 2000). This explains the lack of feedback practices in engineering and science higher education courses, where the lecturers have seldom received educational training (Wankat et al., 2002). Engineering lectures are generally of a passive nature (Mills and Treagust, 2003). The lecturing process usually continues as a passive transmitter-receiver model during the semester, without real evaluation of the students' comprehension of the lectures, i.e. there are no frequent formative assessment practices. As a consequence, students are unlikely to voluntarily reflect on the lectures. This

results in poor comprehension of the learning outcomes, as well as increased cognitive load during the semester as the lecture content becomes more complex and dependent on the previously taught material. A single measurement takes place at the end of the semester when the students take the final exam. This type of measurement is called summative assessment. This form of teaching conforms to the open-loop learning model derived earlier in equation (8.9). A conceptual model of open-loop lecturing is shown in Figure 8.10.

The input of the model is a pulse of information flow (e.g. lasting one hour for a pulse of information) during the lecture. This pulse is repeated every week (if the course comprises one lecture per week), as shown by the green plot in Figure 8.11. The accumulated information delivered by the lecturer is shown by the black plot. The blue plot represents the accumulated information in the student's mind under the impact of the forgetting phenomenon. The simulations show low information retention, i.e. 10% to 20% of the total delivered information.

8.6.2 Model and Simulation of Closed-Loop Lecturing

The closed-loop lecturing mode implies taking and providing frequent *formative assessments* alongside the course progress and continuously facilitating students' feedback and reflection. In the closed-loop lecturing mode, it is made clear to students that they have to practise and that they are knowledge constructors, whilst the teacher's role is to coordinate their learning process. Appropriate teaching and learning techniques should be followed to guarantee the student-centred approach and successful loop closure alongside the semester progress. If knowledge construction is carried out by the students under teacher guidance during the lecturing period, and if this knowledge construction involves effective feedback and reflection during the lecturing period, then this conforms to the closed-loop model and each lecture can be represented by the equation (8.4).

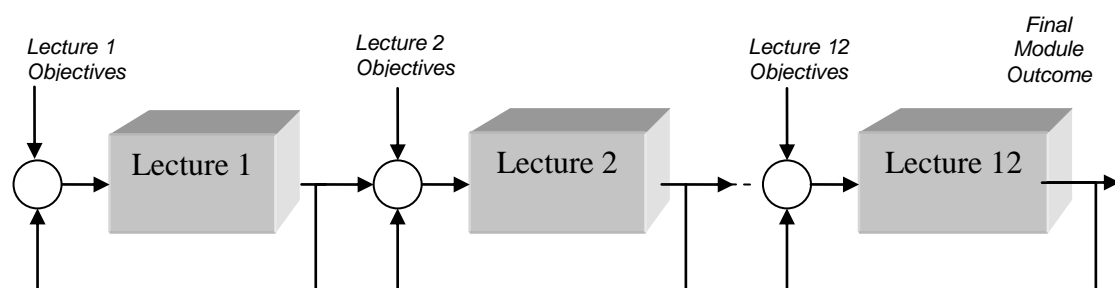


Figure 8.12. Closed-loop lecturing of a course which is modelled as a cascaded process composed of many stages with negative feedback loop for each sub stage.

Let us consider a module comprises 12 lectures spanned over one semester (e.g. one lecture per week for three months). Each lecture aims to accumulate a defined amount of information and depends upon the material learnt in the previous lecture as a prerequisite to reach the new learning objectives. Let's assume that the module is designed in a way that develops effective student feedback and reflection on the taught lectures during the teaching period. Finally, let's assume that the students put effort during the course period into learning, immersing themselves in active experiential learning and continuously practising feedback and reflection. Thus, the lecturing process can be viewed as shown in Figure 8.12 and the complete state space model of the 12 lectures module can be written as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dots \\ \dot{x}_{12} \end{bmatrix} = \begin{bmatrix} -a'_1 & 0 & \dots & 0 \\ 1 & -a'_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & -a'_{12} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_{12} \end{bmatrix} e^{-bt} + \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} r_1 \\ r_2 \\ \dots \\ r_{12} \end{bmatrix} \quad (8.10)$$

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \dots \\ y_{12} \end{bmatrix} = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_{12} \end{bmatrix} \quad (8.11)$$

where $x_i, i=1,2,\dots,12$ are the dynamical internal states representing the constructed knowledge for each lecture, Y represents the measurements of the students actual learning level taken lecture-by-lecture and $r_i, i=1,2,\dots,12$ are the learning objectives of the lectures. Notice that *the system matrix* in (8.10) is a lower triangular; its eigen-values are represented by the main diameter: $\lambda_i = -a_i$ where $i=1,2,\dots,12$. All eigen-values are strictly negative; hence the system is asymptotically stable, which means that in such a model of lecturing, *students are more likely to achieve the set learning objectives*.

As shown earlier in this chapter, the closed-loop model has an inherent robustness characteristic against model uncertainty and the forgetting phenomenon. To show the robustness characteristic, a simulation of average (blue) vs. a 50% weaker student (red) is shown in Figure 8.13. In both simulations, the value of the forgetting factor b was set to 0.005, which is equal to the simulation of the open-loop lecturing model shown in blue in Figure 8.13.

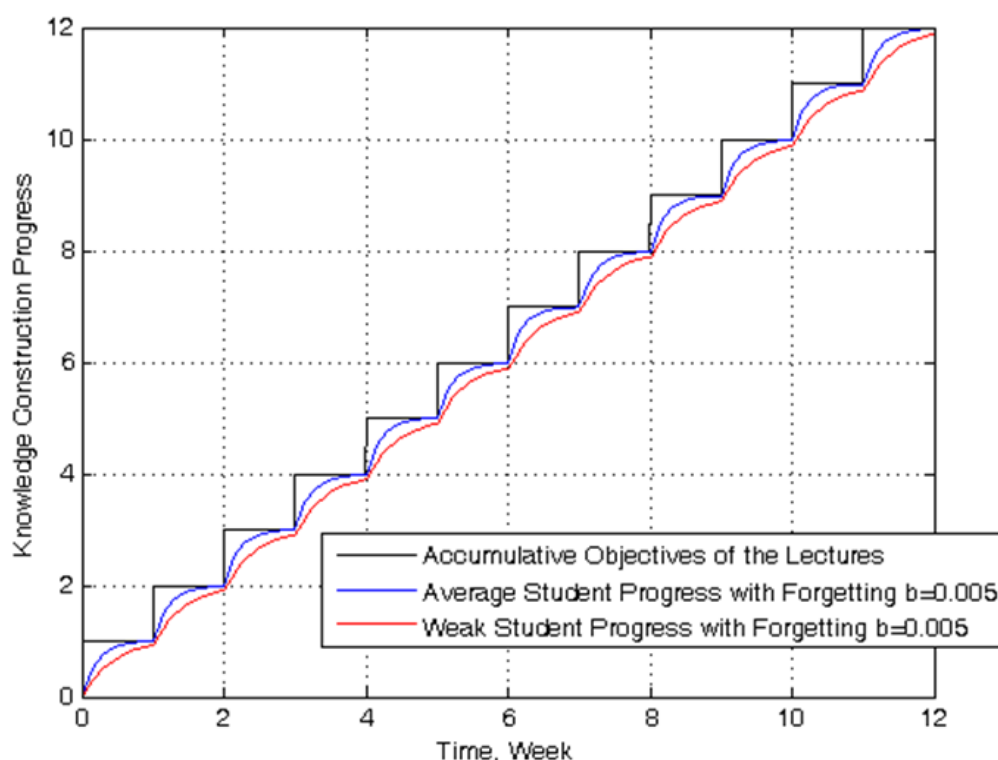


Figure 8.13. Simulation of average vs. weak students' learning performance in the case of closed-loop lecturing.

Despite the lower capability of the weaker students, they could achieve performance close to the average students due to the loop closure. By the end of the module, both students are able to meet the total learning objectives despite the presence of the forgetting factor.

The simulations of the open- and closed-loop lecturing models shows clearly the advantages of adapting modern teaching and learning practices that close the loop; however, this task is not trivial. Closing the loop requires comprehensive assessment and evaluation practices and applying novel constructivist teaching and learning methods. This requires a greater demand on the teacher's as well as elaborated effort. The use of learning technologies and the philosophy of distributed control (e.g. peer assessment and service learning etc.) may assist significantly to overcome these obstacles. In the next section, a demonstration of one technology that can be used to assist in closing the loop in the lecturing process is shown.

8.7 Audience Response System; a Technology to Assist in Closing the Loop in Lectures

An Audience Response System (ARS) comprises of small hand-held remote keypads that transmit students' responses, generally to multiple-choice questions. The students' responses are collected through a receiver and the system is associated with software where the responses can be displayed and analysed. The technology is known by different names such as audience response system (Miller et al., 2003; Banks, 2006), student response system (Johnson and McLeod, 2004; Bunce et al., 2006; Kaleta and Joosten, 2007), classroom response system (Beatty et al., 2006; Fies and Marshall, 2006), group response system (Cutts et al., 2004), personal response system (d'Inverno et al., 2003; Elliot, 2003; Draper et al., 2002; Wit, 2003), electronic voting system (Robinson and King, 2009) and clickers (Barber and Najus, 2007; Duncan, 2005; Wood, 2004; Morling et al., 2008; Alexander et al., 2009).

In this chapter, the system is referred to as the Audience Response System (ARS). Despite the fact that it is a new technology, there have been frequent reports of using ARS in different educational disciplines, including in science and engineering courses (d'Inverno et al., 2003; Roschelle et al., 2004; Wit, 2003; Caldwell et al., 2006; Bunce et al., 2006; Brewer, 2004; Beatty et al., 2006).

The application of the ARS can help to keep the students' attention during lectures. It has been found that students' attention declines steadily during a lecture (Johnstone and Percival, 1976). This may be the main reason that the lecture information is not received effectively by the students. A severe drop in attention after 10-18 minutes from the start of the lecture has been reported (Johnstone and Percival, 1976). One cure for this problem is to prompt the students to think about factual questions repeatedly during the lecture (Middendorf and Kalish, 1996). This can be greatly facilitated by using the ARS. Recent empirical research has found a positive impact of using the ARS on students' learning process (Kennedy and Cutts, 2005). The ARS provides the possibility for all students to participate in a similar active way during the lecture, which has proved to be efficient in the case of shyer students (this is often the case for international students) or students with a speech disorder, for example.

There are many market solutions which provide ARS, such as TurningPoint (2009). A comparison of six commercial products can be found in Barber and Njus's (2007) review. TurningPoint system was piloted in this study and used in classroom settings, many times in combination with remote experimentation in

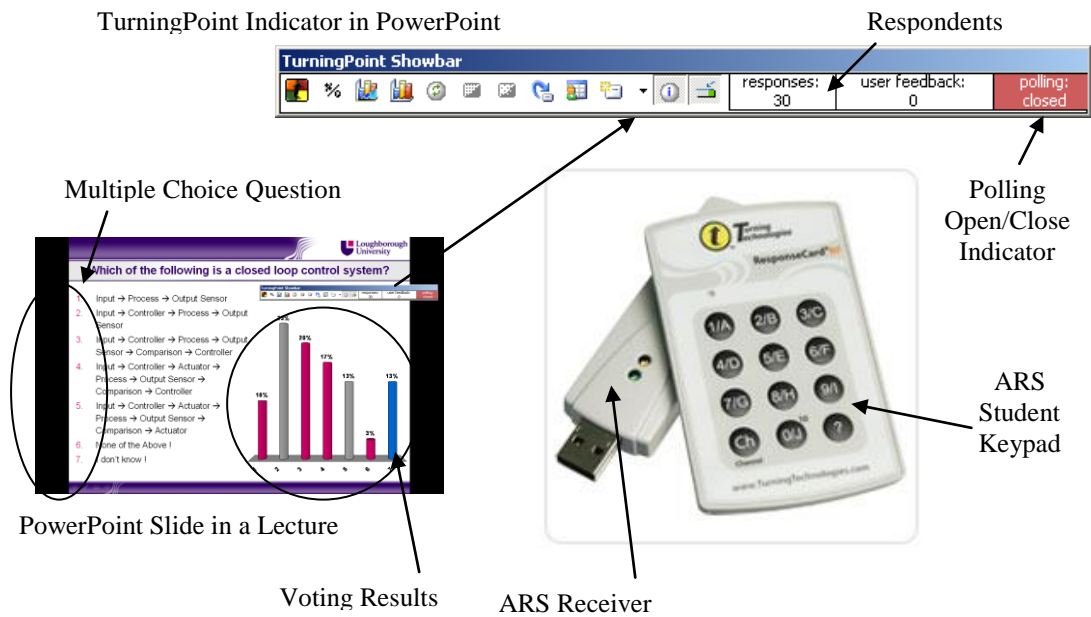


Figure 8.14. Audience Response System (ARS) from TurningPoint.

the lectures, as indicated in Chapter 7. Figure 8.14 shows a keypad of the TurningPoint ARS and the receiver. The keypad transmits radio frequency (RF) signals carrying out the student response to a voting. The RF receiver is a USB device that collects the students' responses and logs them into the TurningPoint software. The latter is a PowerPoint add-on that allows multiple-choice questions to be integrated into PowerPoint presentations, showing the statistics of the students' responses and the correct answer. It also includes a grading system and a comprehensive reporting tool. The software reports or grading can be integrated with a learning management system (LMS) such as Blackboard or WebCT. Each keypad unit has a unique signal; hence, the answers from each individual student can be identified and recorded. The TurningPoint ARS allows rapid response collection, data analysis and results display in an integrated manner with classical teaching equipment such as the PowerPoint presentation with data projector.

The ARS can be an effective tool for closing the loop during the lecture. After 10-20 minutes from the start of the lecture, the students' attention drops significantly, and the teacher may need a clue about the students' comprehension of the taught material so far. Hence, it could be a suitable time to initiate a question poll with the ARS. As the question pops up, the students maintain their attention and probably start a discussion with their peers or look into their lecture materials for help in answering the question. Once the poll closes, the

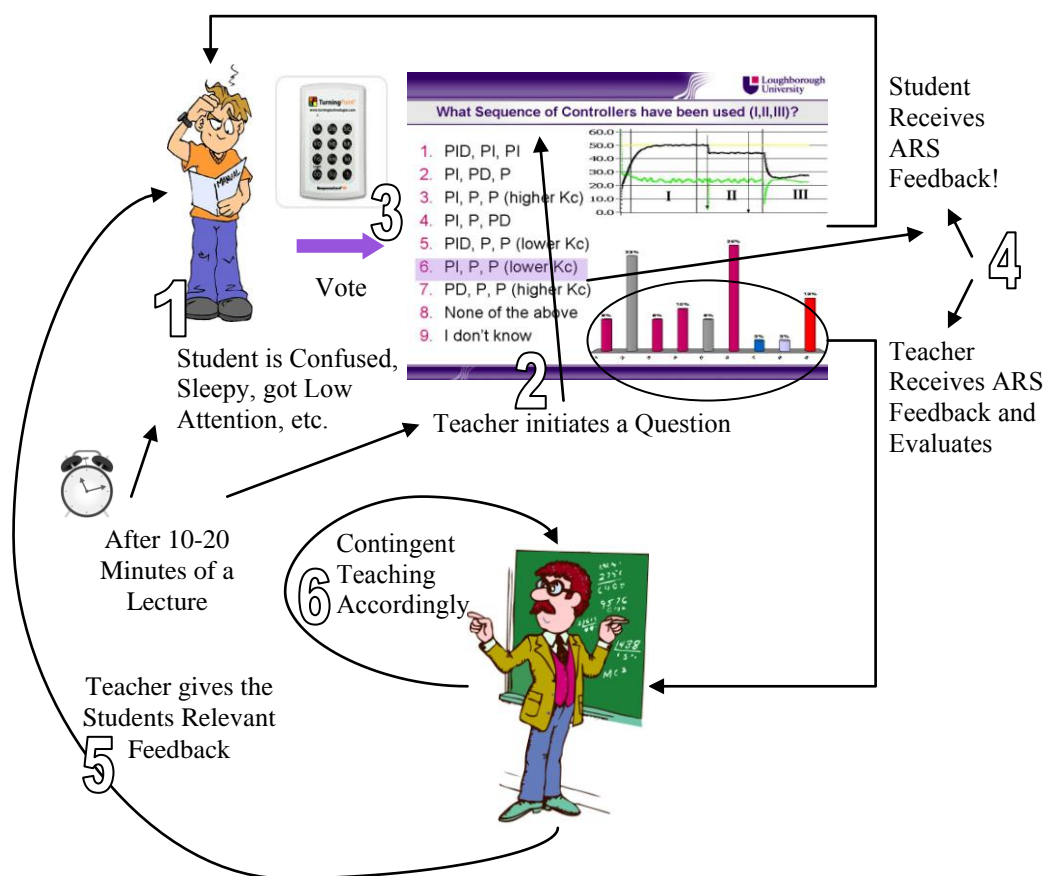


Figure 8.15. Closing the loop during the lecture with ARS.

correct answers may show up (depending on the set-up) and a histogram showing the students' responses also appears. Each student can thus receive prompt feedback of the correct answer and can compare it with his/her choice. The teacher will also receive feedback from the histogram distribution and can decide whether there is a need to deliver further feedback to the class with regard to the asked question or not, or whether there is a need to alter the lecture trajectory. The latter is known in the pedagogical literature as contingent teaching (Draper and Brown, 2004; Wood et al., 1978). The lecture then proceeds and the previous closed loops may be repeated several times. Generally, two to five questions are recommended with ARS during a fifty-minute lecture (Caldwell et al., 2006; Elliot, 2003; Beatty, 2004). This process is shown conceptually in Figure 8.15.

As mentioned in Chapter 7, the TurningPoint ARS has been used during several lectures in the Chemical Engineering Department of Loughborough University, in many cases in conjunction with remote experimentation in the classroom. The system was used with MSc students during the course CGP075 - Advanced Computational Methods for Modelling & Analysis of Chemical Engineering

Systems in February 2008 and in February 2009. A questionnaire was delivered to the students by the end of the course that included questions to measure their attitude towards the ARS and its potential benefits (see Question 1 of Appendix 10 and Appendix 11).

The students' response was very positive. The question had a scale from 1 (Strongly Disagree) to 6 (Strongly Agree) and aimed to measure the students' perception of the impact of the ARS on four dimensions: keeping attention to the lecture; enhancing theory understanding; highlighting the important parts of the lectures; and information retention. The students' responses for both 2008 and 2009 were positive. The mean for 2008 and 2009 show a close result with no statistically significant difference, as shown in Table 8.1. This consistency reflects the positive impact of the ARS on the students' attitude when used in the lecturing process. It also indicates the students' interest in receiving feedback about their learning during the lecture.

The next section gives a review of empirical findings in the pedagogy literature about feedback and links these findings to the developed open- and closed-loop learning models in this chapter.

Table 8.1. Students' attitude to the ARS. Statistical analysis of the means of the responses of MSc students in the February modules of 2008 and 2009. Sample number is 11/9.

Variable	Asymptotic Significance (p-value) of the Mann-Whitney U test	Mean 2008/2009
Keeping Attention	0.157	5.00/5.67
Enhancing Theory Understanding	0.217	4.73/5.44
Highlighting the Important Parts of the Lecture	0.395	4.73/5.33
Information Retention	0.489	4.82/5.33

8.8 Discussion of Empirical Findings in the Literature about Educational Feedback

Stoeger and Ziegler (2007) investigated the impact of using the cyclic SRL model of Zimmerman et al. (1996) on mathematics teaching and learning of fourth grade school pupils in Germany. The model emphasises self-regulatory practices

such as monitoring and self-evaluation, goal-setting and strategic planning, strategy implementation and monitoring and outcome monitoring. The study involved a control group and an experimental group formed from pupils of schools in Germany. The experimental group was trained for five weeks to use SRL techniques during a mathematics course, while the control group received no training. Both groups had to solve similar weekly assignments and quizzes. Two tests were conducted for the students of both groups, the first prior to the training and the second after the five-week period. In the German grading system, the highest grade is 1 and the lowest is 6, where 5 is the failure threshold. The control group students' test results average dropped from 2.37 for test 1 to 3.11 for test 2 ($p\text{-value} < 0.001$) while the experimental group students' test average was stable and showed a small enhancement, 2.68 for test 1 to 2.63 for test 2 ($p\text{-value} > 0.10$). These results show how enhanced closure of the feedback loop leads to a stable performance and eliminates the forgetting factor represented by reduced achievement of the control group in test 2. The study reports that the weak students of the self-regulation training group who had to take an entrance exam to gain entry to a higher school (as they were unable to attain the needed composite score) ALL passed. Normally, 50% score below the pass rate of the entrance exam every year; this was the first time that ALL students passed the entrance exam. This indicates that enhanced closure of the loop reduced the gap between the weak and average students. The analysis of the weekly assignments and quizzes of the students in the experimental group revealed a linear increase in the solution rate of the mathematical problems over the course of the five weeks; the linear growth slowed down towards the end of the training. These findings are compatible with the growth of the closed-loop learning curve, as shown in Figure 8.9.

McKinney et al. (2009) investigated the learning outcomes of listening to psychology lectures via podcasts without lecture attendance (experimental group) vs. attending the lecture but no podcasts (control group). The results were reported through the average means and standard deviation (SD) of the groups. About two thirds of the experimental group students listened to the recording of the lecture twice or more (more cycles), while the control group students had only one access to the lecture via attendance (they were not provided with audio records). Both groups were tested; the experimental group average was 71.24% (SD = 16.50%) while the control group average was 62.47% (SD = 17.03%), with $p\text{-value} < 0.05$, indicating a statistically significant difference. Within the experimental group there were students who took notes alongside the lecture and students who took no notes. The comparison of the test

results between the two groups (notes, no notes) revealed an average 76.23% (SD = 13.61%) for the note-taking group and 62.08% (SD = 17.93%) for the no notes group. Listening to a lecture more than once and/or taking notes are practices of cyclic learning and involve more reflection and feedback than listening to a lecture once or taking no notes (open-loop learning). McKinney et al.'s (2009) findings support the closed-loop learning model hypothesis of enhanced learning vs. the open-loop learning model. Furthermore, the standard deviation (SD) in that study shows that the more feedback and reflection is practiced by learners, the lower the dispersion or gap in achievement is among the group members (i.e. more convergent learning outcomes).

Krause et al. (2009) conducted a controlled experiment on the effect of feedback intervention on e-learning in a statistics course. The control group students worked on six problem-solving tasks on correlation analysis. Once a task was completed, students had access to a worked example of the same nature so they could evaluate their solutions, thus the control group students had some feedback available. The experimental group students were exposed to the same procedure plus an additional feedback treatment composed of six multiple-choice tests with adaptive and elaborated feedback. On a scale of 20, the pre-test of the control and experimental group showed equivalence, 4.28 (SD = 2.13) for the control group, 4.24 (SD = 2.33) for the experimental group with $p\text{-value} > 0.05$. The post-test, however, revealed a significant impact of feedback intervention on students' learning. The control group students averaged 10.25 (SD = 3.41) while the experimental group students averaged 14.51 (SD = 2.15) with $p\text{-value} < 0.05$. Furthermore, analysis of the students results in terms of low- and high-level prior knowledge show that feedback benefited low-level students significantly in bridging the gap and reaching a level similar to the high-level students in the post-test. In the control group, the low-level students averaged 8.85 (SD = 3.63) in the post-test and the high level students averaged 12.25 (SD = 1.81) with $p\text{-value} < 0.05$, while in the experimental group, the low-level students averaged 14.25 (SD = 1.92) and the high-level students averaged 14.84 (SD = 2.5) with $p\text{-value} > 0.05$. Krause et al.'s (2009) findings support the hypothesis of the closed-loop model that better enhancement of loop closure leads to higher achievement and bridges the gap between students of different levels.

8.9 The Abdulwahed-Nagy Model as an Enabler of Closed-Loop Learning

In this section, an interpretation of the pedagogical findings in Chapter 6 in light of the closed-loop learning model is presented.

8.9.1 Kolb's Learning Cycle as a Closed-Loop Learning Model

Kolb derived his model based on Lewin's social and pedagogical works (Lewin 1942; Kolb, 1984). Lewin borrowed the control engineering concepts such as reference signals, measurements and feedback to develop a four-stage model of learning that later became the core basis of Kolb's experiential learning theory (Kolb, 1984). Lewin considered information feedback an essential element in building a continuous process of goal-directed learning actions. Lewin and his followers firmly believed that much of the deficits of individuals and organisations could be traced to a lack of feedback processes (Kolb, 1984). Kolb emphasised many times that learning should be considered as a continuous *process* grounded in experience. He defines learning as a *process of constructing knowledge*. Brandt (2007) considers Kolb's experiential learning theory as a cyclic model of control systems.

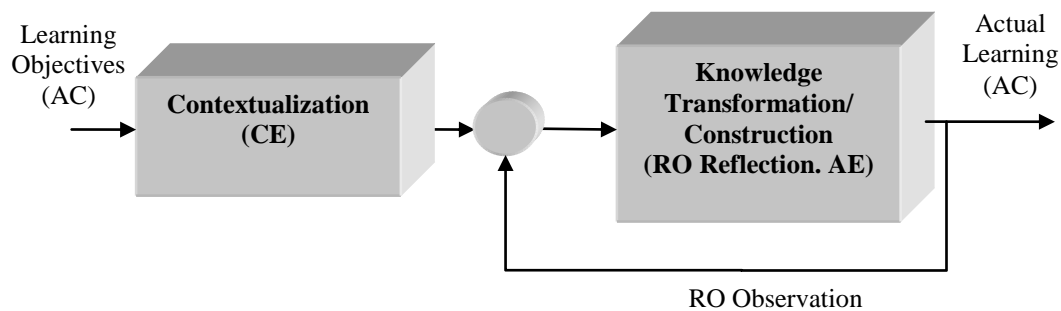


Figure 8.16. Mapping Kolb's cycle into a closed-loop engineering model.

Let's recall Kolb's experiential learning theory from Chapter 2. Kolb proposed that constructivist learning should pass through a cycle comprising four main stages: Concrete Experience (CE); Reflective Observation (RO); Abstract Conceptualisation (AC); and Active Experimentation (AE), as shown in Figure 2.2. The CE stage is reported as a place for stimulating and contextualizing the learners' attention towards the intended learning outcome (Bailey et al., 2004); it represents the first exposition to new knowledge or experiences. The CE would work as a filter, contextualizing the learner into a filtered set of learning objectives. Knowledge construction (the integrator) is achieved via active

experimentation (AE) and reflection (RO). This construction results in new abstract conceptualisation (AC) in the learner's mind that maps internally the external abstracts (AC) given in the input (learning objectives). The observation (RO) phase evaluates the constructed abstracts and feed backs to the learner information about whether a subsequent cycle of construction is needed to meet the learning objectives or not. The loop keeps on running until the whole set of learning objectives are met. Mapping Kolb's experiential learning cycle into a closed loop model is shown in Figure 8.16.

8.9.2 *The Match of the Empirical Data with the Closed-Loop Learning Model*

Let's recall the Abdulwahed-Nagy model of constructivist laboratory education, as shown in Figure 6.20. The model builds thoroughly on Kolb's experiential learning theory and presents an iterative process of learning which facilitates knowledge construction, feedback and reflection via the different associated activities. It was shown in the previous subsection that Kolb's cycle can be considered as a closed-loop learning model. In comparing the learning outcomes of the students of the control and experimental groups, enhanced achievement has been recorded in all of the six measurements taken, as shown in Figure 8.17. 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% (SD = 17.74, N = 35, p-value = 0.000 < 0.05). In the pre-lab tests of Week 2 the control group students' average was 28.55% (SD = 19.52, N = 59), while the experimental group students' average was 43.04% (SD = 20.75, 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% (SD = 19.87, N = 36, p-value = 0.000 < 0.05). In the post-lab tests of Week 2, the control group students' average was 41.84% (SD = 22.02, N = 57), while the experimental group students' average was 58.37% (SD = 19.66, N = 30, p-value = 0.001 < 0.05). For the laboratory report mark, the control group students' average was 63.03% (SD = 7.42, N = 65), while the experimental group students' average was 67.28% (SD = 5.19, N = 46, p-value = 0.002 < 0.05). For the mark of the final exam of the module, the control group students' average was 48.40% (SD = 21.27, N = 65), while the experimental group students' average was 58.47% (SD = 20.40, N = 46, p-value = 0.018 < 0.05). A summary of the statistics is shown in Table 8.2.

The way the model was applied included one major iterative learning phase through the pre-lab preparation session, which was conducted with the virtual

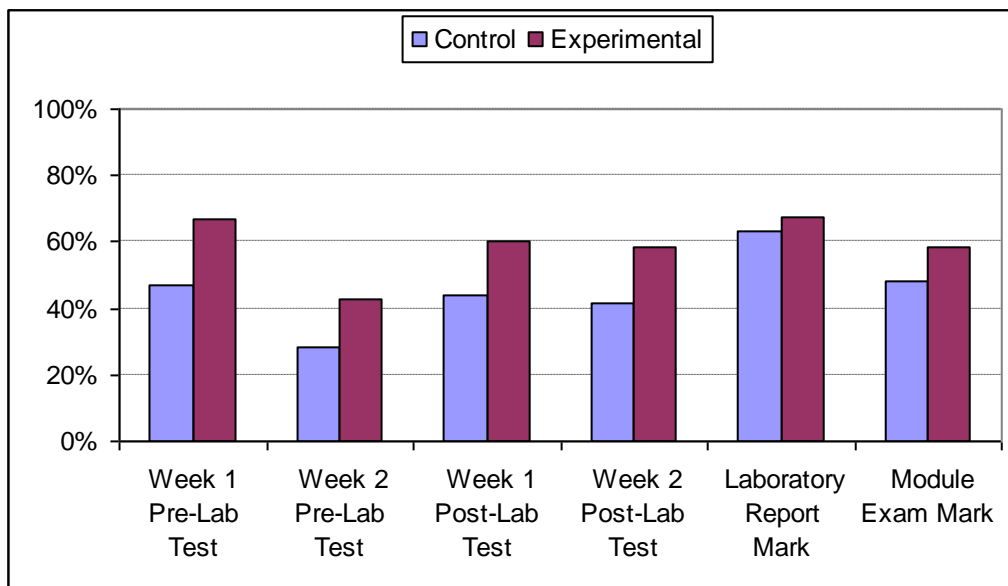


Figure 8.17. Individual means of the six measures of learning outcomes of the control and experimental groups of the investigation in Chapter 6. The experimental group students scored higher than the control group students in all measures.

lab software. However, this single opportunity of cyclic learning significantly enhanced the students' learning outcomes.

Table 8.2. 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	SD	p-value	Statistical Significance
Pre-lab test of Week 1	56/35	47.2/66.8	20.8/17.7	0.000	Yes
Pre-lab test of Week 2	59/35	28.6/43.1	19.5/20.75	0.000	Yes
Post-lab test of Week1	58/36	44.1/60.1	19.2/19.87	0.000	Yes
Post-lab test of Week 2	57/30	41.8/58.4	22.1/19.66	0.001	Yes
Laboratory report mark	65/46	63.0/67.3	7.4/5.19	0.002	Yes
Final exam mark	65/46	48.4/58.5	21.3/20.4	0.018	Yes

All the six measurements conform to the closed-loop model prediction of enhanced learning outcomes due to further activation of feedback and cyclic learning. The averages for all six measures were higher for the experimental group with statistical significance. Four of the six measurements show reduced standard deviation of the experimental group outcome, which conforms to the closed-loop learning model.

Let's recall section 7.7.4, where a feedback lecture was conducted with remote experimentation and the use of the ARS in an undergraduate course was presented. Figure 7.10 reveals its closed-loop nature. The outcomes of the quizzes, shown in Figure 7.11, demonstrate the enhanced learning of PID theory as a result of feedback intervention.

The ways of implementing pedagogical feedback can be as diverse as the ways of implementing technical feedback. The next section discusses some other ways of closing the loop.

8.10 Other Ways for Closing the Loop

Many methods can be used to close the loop in the learning process, i.e. for establishing feedback. Enhanced loop closure can be achieved by pedagogical modifications of the learning or educational process, the use of learning technologies, or by a mixture of both. Pedagogical modifications may include using more frequent formative assessment, training students on self-regulated learning skills, establishment of effective feedback and systematically designing the instruction or curricula. Learning technologies can play an essential role in closing the loop and facilitating cyclical learning. Simple technologies such as recorded audio lectures played on an mp3 player can be significantly effective (McKinney et al., 2009; Rossiter et al., 2009). Assessment in e-learning has been proposed as an enabler of SRL (Mandl and Krause, 2003). An efficient electronic self- and peer- assessment system is WebPA (Willmot and Crawford, 2007; Loddington et al., 2009). Learning technologies can help to implement automatic feedback schemes. Automatic feedback is much more economic than teacher feedback and can accommodate a high number of students in shorter time (Krause et al., 2009).

8.11 Towards Systems Pedagogy

Control engineering is the nerve that led to innovation and industrial revolution (Åström and Murray, 2008). In the information age, control theory continues to

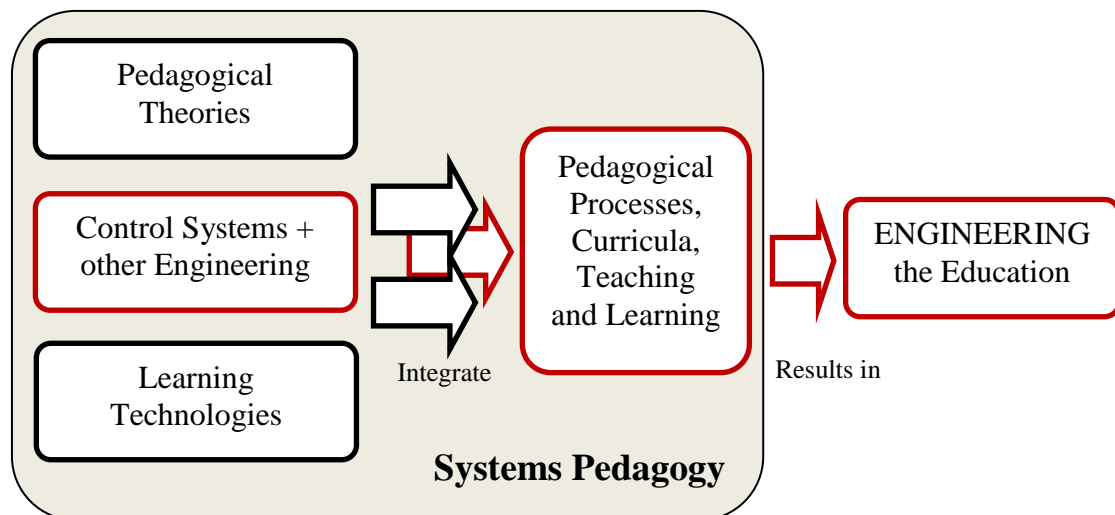


Figure 8.18. Block diagram model of the 'Systems Pedagogy' concept.

penetrate unconventional areas such as software engineering, economy, Internet flow control, nano-technology and finance etc. (Murray et al., 2003). Control engineering is a very multidisciplinary field and has made use of many tools from mathematics, physics, artificial intelligence and systems theory etc., and applied them successfully to a wide spectrum of areas. The theory keeps growing and evolving on a continuous basis. In this thesis, the utilisation of control systems theory has been applied to pedagogy for the purpose of modelling and understanding a class of pedagogical processes. Control systems theory as a multidisciplinary field and as a systematic approach for engineering systems to behave in a desired way can be used as a framework of a so-called *Systems Pedagogy*.

In this thesis, 'Systems Pedagogy' is proposed as a new multidisciplinary field of science that incorporates control systems theory with pedagogy, cognitive psychology, learning technologies and artificial intelligence to produce a new systematic mixed method (quantitative and qualitative) educational theory such as shown in Figure 8.18. The theory's main target is to develop dynamical models of pedagogical processes, verify them and utilise them to design control strategies for achieving a stable and optimal outcome. In technical systems, control engineers rely on physics to derive the models. The physics that the 'Systems Pedagogy' engineers utilise is found in pedagogy, cognitive science and psychology. 'Systems Pedagogy' is based on science, but it is an engineering-oriented field whereby it is concerned with designing educational systems that are optimal and stable out of existing elements. Just as technology, i.e. sensors,

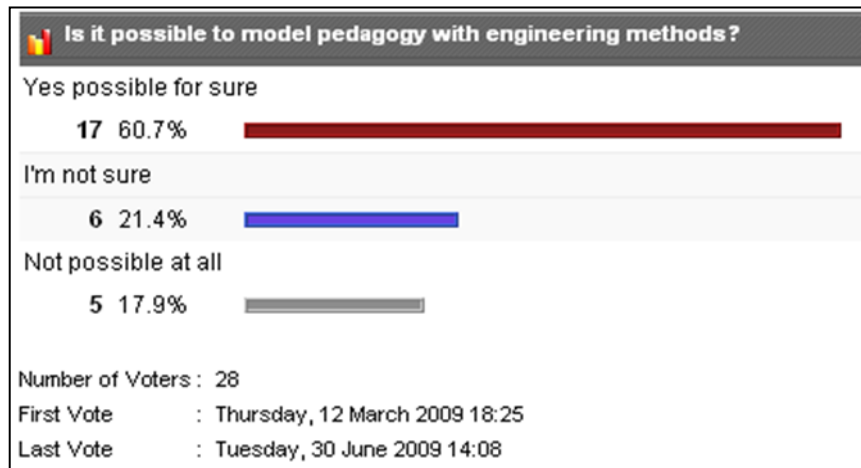


Figure 8.19. Response of delegates of STEM PRM 2009 symposium on what they think about using engineering methods for modelling pedagogy.

actuators, computational algorithms etc., played a vital role in realising modern control engineering designs, learning technologies and ICT will play an essential role in implementing systems pedagogy. The ultimate aim of ‘Systems Pedagogy’ is to produce adaptive self-regulated learning processes that minimise (or eliminate), at a certain stage, the need for the teacher or the school to acquire learning.

The approach of engineering and modelling the pedagogy in mathematical terms could be controversial, particularly among educationalists (Yeung, 2006). However, engineers seem less sceptic and are even somehow motivated, according to our observations of the responses to this philosophy in engineering education conferences when models of this chapter were presented (e.g. in ICEE 2008, FIE 2008 and AAEE 2009). Furthermore, the survey of the STEM PRM 2009 Symposium website, where most of the delegates were of a science or engineering background, showed that 60.70% of the delegates are sure that pedagogy can be modelled with engineering methods. Only 17.9% of the delegates expressed the opinion that it is not possible at all to model pedagogy with engineering methods, as shown in Figure 8.19. This enthusiasm for the concept by the engineering community can be explained by the fact that engineers are activists. Engineers are trained to impact the world by designing effective systems that never existed before out of existing elements. Nevertheless, nurturing the concept of ‘Systems Pedagogy’ or ‘ENGINEERING the Pedagogy’ requires collective co-operation between interested academics and researchers from engineering and from pedagogy, as well as the availability of

funding. The engineering education research community already consists of engineers and educationalists; hence, it is the most suitable venue for advancing the ‘Systems Pedagogy’ concept.

8.12 Conclusions

This chapter introduced a novel approach of using control systems methods for modelling pedagogical processes. The argument of why control systems mathematical models of pedagogy should be developed has been expressed. The case for modelling learning was then developed with concentration on two extremes so-called open- and closed-loop learning. The modelling process of learning was made in a similar way to engineering modelling; the tank example was selected for illustration. The analysis of the models showed the advantages of the closed-loop learning model vs. the open-loop learning model in conjunction with three main issues. The closed-loop learning process is stable, holds an inherent disturbance rejection mechanism (e.g. forgetting) and is robust. A new model of forgetting, based on engineering concepts, was introduced. The open- and closed-loop learning models were applied to the lecturing process to show their implications to the learning dynamics of a course taught over one semester. A section on using the audience response system (ARS) as a technology for closing the loop in the lecture was presented. A survey of the students’ opinion of the ARS, showed a positive attitude. This was followed by a discussion section with supportive empirical findings of the closed-loop learning model prediction in the pedagogical literature. A link between the findings in Chapter 6 and the closed-loop learning models was presented. The chapter ends with a proposal for ‘Systems Pedagogy’ as a multidisciplinary field of science which aims to engineer the educational sciences and design.

Chapter 9.

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

9.1 *Summary of the Findings and Contributions*

The literature review in Chapter 3 revealed that there is a lack of empirical studies in laboratories and in particular virtual and remote labs. Furthermore, it has been found that laboratory teaching and learning design is seldom built thoroughly on constructivist educational theories. The reviews have shown that hybrid laboratory structures are recommended compared to sole dependence on the hands-on approach in teaching and learning. Nevertheless, very few academic studies report the utilisation of hybrid labs. None have reported the use of the three modes together.

Chapter 5 provided the proposal of the TriLab as a triple access mode laboratory where virtual, hands-on and remote labs are combined through one software package. It was shown that LabVIEW is a suitable platform for developing the TriLab in Chapter 3, and the development of the Armfield modular system of the Loughborough Process Control Lab was detailed in Chapter 5. Joomla, a novel web development tool for efficient dynamic websites, has been used to deploy the iLough-Lab, the first remote laboratory portal of Loughborough University and one of the few in the UK (iLough-Lab, 2009).

A pedagogical hypothesis to explain the generally reported poor learning outcomes of hands-on labs was proposed in Chapter 6. The hypothesis builds upon Kolb's experiential learning theory and explains the weak outcomes as a result of weak activation of the learning cycle dimensions. A special educational experimentation design of control and experimental groups was performed and comprehensive data analysis conducted for two consecutive years of students' pre- and post-lab tests, marks of the laboratory report and marks of the final exam of the module have been detailed. The findings confirm the hypothesis and show that students who have better activation of the prehension dimension have

better activation of the knowledge transformation dimension of the learning cycle proposed by Kolb. Activating the prehension dimension was achieved mainly by using the virtual lab component of the TriLab model in a pre-lab preparation session. The students' survey findings emphasise the important role of the Process Control Lab and show that it left a positive impact on the students. A proposal for a constructivist laboratory education model that integrates elements of the TriLab in the light of Kolb's experiential learning theory has been made. The model was well received at the FIE 2008 conference and was published in a high quality educational journal (Abdulwahed and Nagy, 2009a). This is one of the few available models of laboratory education that builds thoroughly on a pedagogical theory.

Chapter 7 discussed using the remote component of the TriLab in classroom teaching and learning. Experiments in the classroom were used to support the lecture theory, and the student survey showed the positive impact of this approach with a consistent outcome over two years. The practice of using remote experiments in the classroom is not widespread; the evaluation of its impact is seldom reported. Hence, this thesis is one of the first works that provides an analysis of the impact of bringing the laboratory into the classroom through remote experimentation.

Chapter 8 introduced the use of control systems methods for modelling teaching and learning. In particular, learning was perceived as an accumulating process of knowledge construction, and two extremes (open- and closed-loop learning) were modelled. Open-loop learning model conforms to the classical passive approach, while closed-loop learning model conforms to constructivist, self-regulated and feedback rich approaches. The models show mathematical and engineering evidence of the importance of feedback on learning. The proposal of 'Systems Pedagogy' as a new pedagogical paradigm has been laid down. The approach of using engineering methods, such as control systems, for modelling and designing effective learning processes was well received by the audience in FIE 2008, ICEE 2008 and AAEE 2009 conferences. A relevant paper was selected as one of the top papers at EISTA 2008 for publishing in a refereed academic journal (Abdulwahed et al., 2009). This is probably the first time that control system engineering has been used for modelling in pedagogy.

9.2 Towards Rigorous Research in Engineering Education

As discussed in Chapter 1, research in engineering education is at an emergent status and is still in the process of rigorous establishment (Streveler and Smith,

2006; Borrego, 2007). The following criteria for defining rigorous research in engineering education are stated by Streveler and Smith (2006):

1. Pose significant questions that can be answered empirically.
2. Link research to relevant theory.
3. Use methods that permit direct investigation of the question.
4. Provide a coherent and explicit chain of reasoning.
5. Replicate and generalise across studies.
6. Disclose research to encourage professional scrutiny and critique.

In response to these criteria, significant questions were posed in Chapter 6 and answered empirically. Linkage of research to pedagogical and engineering theories has been achieved throughout Chapters 6, 7 and 8. The findings were based on direct measurements by using tests, questionnaires and in-classroom quizzes. It is hoped that the thesis has provided a coherent and explicit chain of reasoning. The three reviewers of the JEE article (Abdulwahed and Nagy, 2009a) had very positive attitude towards the structure and reasoning of the hypothesis. Generalizability of engineering education research can be achieved via linking the investigation with appropriate educational, psychological, and sociological theory (Streveler and Smith, 2006). This has been done throughout the thesis. Finally, the findings have been disclosed in a number of journals and conference papers as well as a web portal.

Streveler and Smith (2006) indicate that the engineering faculty involved in engineering education research have the potential to *contribute* to learning theory, and not only informed by it, through collaboration with learning and social scientists. It is hoped that Chapter 8 has contributed to the body of knowledge of learning theories.

9.3 Recommendations and Future Work

In light of this work, modifications are planned to the structure of conducting the Process Control Lab sessions for undergraduate courses. A compulsory and marked pre-lab assignment will be imposed. The assignment will contain a preparatory quiz to be solved by following the lab experimental procedures with the virtual lab software. This intends to replace the necessity of scheduling pre-lab preparation sessions. Pre- and post-lab tests will be compulsory and their marks will contribute to the final assessment of the laboratory coursework. The practice of using experiments in the classroom will continue, potentially

assigning homework readings to compensate for the time needed to do the experiments in the classroom.

Joomla will be recommended to build collaborative laboratory environments for enhancing distributed team-work in conducting remote experiments. It will be recommended also to deploy Joomla-based Web 2.0 capabilities such as wiki, forum and profiling to enhance students' interaction around the experimental work. Game engines (Chang et al., 2007) or 3D multiuser virtual worlds (Second Life, 2009) can be used to create immersive virtual and/or remote laboratory environments.

9.4 Conclusions

In this thesis, novel models of laboratory education have been developed. From the technology contribution viewpoint, the TriLab model has been proposed and an implementation example of the Process Control Lab has been demonstrated, using LabVIEW and Joomla to develop an online laboratory portal. From the pedagogical contribution viewpoint, a novel constructivist laboratory model, based on Kolb's experiential learning theory, has been introduced. Additionally, blending theory lectures with remote experimentation has been investigated and found to leave a positive impact on students' learning and understanding. Similarities between many areas of pedagogical research and feedback control systems have been identified. A novel utilisation of control theory for modelling pedagogy has been shown. Finally, recommendations and future plans of work in the related area are proposed.

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Appendix 1

Virtual, Hands-on and Remote Laboratory Papers from Ma and Nickerson' (2006) Review

Articles in red are those who could not be accessed by the thesis author.

Hands-on	Virtual (Simulated)	Remote
Grant (1995)	Chetty and Dabke (2000)	Tan et al. (2000)
Collins (1986)	Fernandez-Inglesias et al. (2000)	Hutzel (2002)
Fisher (1977)	Sehati (2000)	Gustavsson (2003)
Faucher (1985)	Ertugrul (1998)	Vial and Doulai (2003)
Edward (2002)	Wicker and Loya (2000)	Naghdy et al. (2003)
Magin and Kanapathipillai (2000)	Smith and Pollard (1986)	Krehbiel et al. (2003)
Magin (1984)	Garcya-Luque et al. (2004)	Shen et al. (1999)
Elton (1983)	Edward (1996)	Arpaia et al. (2000)
Berg et al. (2003)	Dobson et al. (1995)	Ferrero et al. (2003)
Tapper (1999)	McAteer et al. (1996)	Albu et al. (2004)
Martin and Lewis (1968)	Magin and Reizes (1990)	Gustavsson (2002)
Martin (1969)	Shin et al. (2002)	Bauchspiess et al. (2003)
Miller et al. (1998)	Gomes et al. (2000)	Colwell et a. (2002)
Beck (1963)	Raineri (2001)	Scanlon et al. (2004)
Drake et al. (1994)	Edleson et al. (1999)	Zimmerli et al. (2003)
Roth et al. (1997)	Budhu (2000)	Arpaia et al. (1997)
Wentz and Snyder (1974)	Ertugrul (2000)	Thakkar et al. (2000)
Schauble et al. (1995)	Karady et al. (2000a)	Ko et al. (2000)
Kozma et al. (2000)	Karady et al. (2000b)	Rohrig and Jochheim (2001)
Feisel and Rosa (2005)	Sakis Miliopoulos and Cokkinides (2000)	Kolberg and Fjeldly (2004)

Appendix 2

Manual of the Instrumentation and Control Laboratory

This appendix presents the manual of Instrumentation and control laboratory that is used during the laboratory sessions of the second year course Instrumentation, Control, and industrial Practice.

1. INTRODUCTION

The laboratory is an introduction to the dynamic behaviour of pilot-scale equipment and the operation of a feedback controller. The principle aim is understand the role and operation of the main components in a feedback loop: (i) sensor, (ii) actuator (control valve) and (iii) controller.

The plant to be controlled is a liquid surge tank with a pump in the outlet stream. To an acceptable approximation (which will be tested in the laboratory), the liquid flow from the tank is independent of the liquid level in the tank. The flow of liquid entering the tank is independent of the tank's liquid level; as a consequence, the tank acts as an integrator, integrating the difference between the flow in and the flow out. Control action is needed to stabilize the liquid level by making one of the flows dependent on the liquid level.

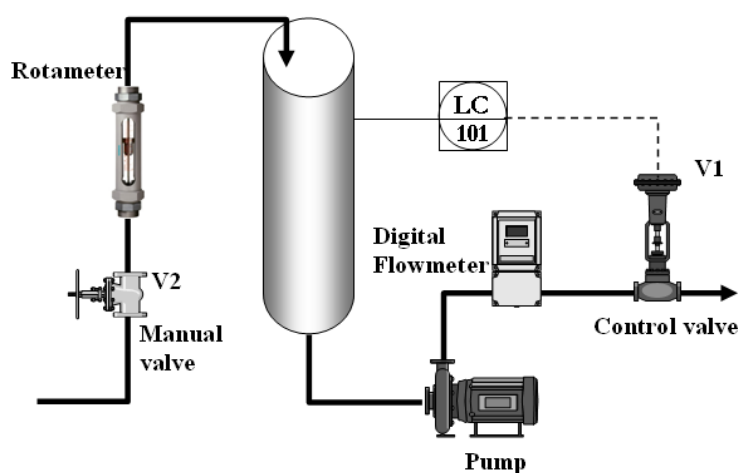


Figure 1. Simplified Diagram of a Surge Tank Control System

2. OBJECTIVES

A. Week 1

- A1. Calibrate the level sensor.
- A2. Calibrate the control valve. Study the installed characteristics of a valve.
- A3. Study the effect of hysteresis in the control valve and sensor.

B. Week 2

- B1. Understand the dynamic behaviour of the system
- B2. Evaluate manual control.
- B3. Evaluate the tuning of a PID control via manual and automatic tuning
- B4. Evaluate the effect of positive or negative feedback on the closed-loop system

3. ORGANIZATION AND PREPARATION

You are expected to prepare for the Laboratory!

Before practical work can start, the Laboratory Supervisor will want to see evidence of your preparatory work. This can be in the form of *initial experimental plan* and *observations* collected using the “Virtual Process Control Rig”, **summarized in your laboratory notebook.**

Experimental work is performed by pairs (or groups of three) of investigators working on a specific rig in the Control Laboratory. Each pair of investigators is responsible for starting their apparatus at the beginning of the laboratory and shutting down the equipment before leaving the laboratory. The nominal procedures in Appendix A can be adapted to the characteristics of each individual rig.

- *Before the timetabled practical session:*

1. prepare a laboratory notebook where you will record all observations during preparation and the experiments
2. read these notes carefully
3. download from the LearnServer the installation kit of the “Virtual Process Control Laboratory” and familiarize yourself with the software and procedure.

- *Preparation in the lab*

4. Trace all lines (pneumatic, electrical, hydraulic) on the rig.
5. Before turning on the input flowrate, observe the action of the control valve. Set the control mode to MANUAL on the software interface and

adjust the input signal to the valve between 0 and 100%. Record whether the valve opens or closes when you increase/decrease the signal.

6. Test the approximation that the output flow is independent of the water level in the tank. Set the control valve on MANUAL mode, completely open and adjust the input flow rate to achieve a steady low level in the tank. Record the output flow rate. Increase the input flow rate and adjust it to achieve a steady high level. Record the output flow rate in this case. Is there a difference between the maximum output flowrates in the two cases? After this procedure establish a steady state at about 30-50 % level and record the steady state operating conditions in your laboratory notebook.
7. Using a computer drafting package, construct a piping and instrumentation diagram (P&ID) for the experimental rig. Label all manual valves.
8. Develop an experimental procedure.

4. EXPERIMENTAL PROCEDURE

I. Sensor Calibration

Introduction

A level sensor is an essential element in all chemical plants. The signal obtained from the device is usually a standard electric signal (e.g. 0-5 V). This value needs to be correlated with the real level in the tank to obtain the desired information. This process is called **calibration**. For appropriate level control and monitoring the characteristics of the level sensor needs to be determined. The level sensor is a linear device, which may exhibit hysteresis in the output. The output (voltage) can be related to the input (level) by the equation:

$$Level(\%) = K_s \cdot Voltage(V) + Z_s \quad (1)$$

where K_s is called the sensor's *Gain* (defined as change in the Output over change in the input) and Z_s is the *Zero* of the instrument.

Calibration Procedure

1. First, determine the range of operation of the sensor's input variable (i.e. the liquid level) and output variable (i.e. the voltage sent to the controller). This is done by:
 - a. Setting the controller on AUTO mode and changing the setpoint on the computer (0 to 100%) until the water level has stabilized at the desired MAXIMUM level in the tank (e.g. just below the overflow in the tank), and noting the value of the measured signals (signal in voltage and level in %).
 - b. Applying a similar procedure but changing the setpoint on the computer until the level stabilizes at the desired MINIMUM level in the tank (e.g. at or slightly above the bottom of the tank)
2. Starting from the liquid level and setpoint identified in step 1 above, change the setpoint progressively to a number of values (approximately 10) to adequately cover the range of operation identified above. When the system stabilized at the new setpoint RECORD the liquid level (in %) which is the input to the sensor, and the measured signal (Voltage) which is the output of the sensor. Measure the input and output variables at sufficiently many points (approximately 10) between the extremes of operation.
3. To assess the extent of hysteresis calibrate the sensor using strictly increasing liquid levels and then reverse the process using falling liquid levels. This can be achieved easily by setting the controller on a Manual mode. If the tank has the minimum level, close the control valve completely. Due to the constant input flow the level will increase steadily until the maximum level is reached. When the maximum level is reached open the control valve completely and turn off the input flowrate. The level will decrease continuously. Use this data to perform calibration. Since the values used in this procedure are not steady state values (they change continuously) the procedure is called dynamic calibration.
4. Plot the calibration curve (level versus voltage) and determine the gain and zero of the instrument by fitting a line to the experimental data. Perform separate fittings of the increasing and decreasing data, as well as using all data points. Compare the three calibration equations with each other and with the calibration obtained using the data at point 2.

II. Calibration and Characteristics of the Control Valve

Introduction

A control valve is a device which allows to change flow resistance, through a changing external input signal. A control valve changes the flow of a fluid by altering the valve's flow resistance.

A control valve consists of two main components:

- the *valve actuator* (which accepts an external signal and changes the valve stem position) and
- the *valve body* (which contains a movable plug attached to the valve stem). By partially blocking the valve orifice with the valve plug, a variable flow resistance is obtained.

Valve Actuator

Most valve actuators (including those found in the Control Laboratory) are linear devices, altering the valve stem position, x , in response to a change in an input signal, u :

$$x = a \cdot u + b \quad (2)$$

where a and b are constants. The stem position varies between $x = 0$ to $x = x_{\max}$. The maximum stem travel, x_{\max} , varies from actuator to actuator; as a consequence, a dimensionless valve stem position, is defined by:

$$l = x / x_{\max} \quad (3)$$

such that

$$l = 0 \text{ at minimum flow rate} \quad (4)$$

$$l = 1 \text{ at maximum flow rate} \quad (5)$$

The valve action determines the values of a and b in (2).

Valve Action

Control valves have two main types of *action*. They either

- *Fail Open* (FO), producing maximum flow at minimum signal, giving

$$l = \frac{u_{\max} - u}{u_{\max} - u_{\min}} \quad (6)$$

- or *Fail Closed* (FC), producing minimum flow at minimum signal, giving

$$l = \frac{u - u_{\min}}{u_{\max} - u_{\min}} \quad (7)$$

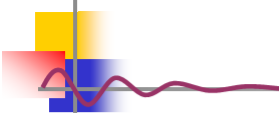
where u_{\min} and u_{\max} are the minimum and maximum values of the external input signal. Usually this signal is electric or pneumatic. In our case we can consider a range of 0-100%.

Valve Characteristics


The valve body contains an orifice, through which fluid flows, and a movable plug, which obstructs the flow. Valves are distinguished by their characteristic, which is the variation in the fluid flow through the valve as the valve plug is moved. Differently shaped plugs give different valve characteristics. Motion of the valve plug is reported as changes in the fractional valve stem position, l .

Inherent Characteristics

The inherent characteristic of a valve is given by the flow behaviour through the valve when the pressure drop across the valve body is constant. For fully turbulent liquid flows, the inherent characteristic is reported using the valve sizing coefficient, C_v or K_v , which is the flow of water at unit pressure drop across the valve body. An overview of the basic valve equations is given below.



Basic valve equations



$$C_v = \frac{q(\text{GPM})}{\sqrt{\Delta P(\text{PSI}) / g_s}}$$

$$K_v = \frac{q(\text{m}^3 / \text{h})}{\sqrt{\Delta P(\text{bar}) / g_s}}$$

- C_v, K_v – valve coefficient
- Where q is volumetric flow rate
- g_s - specific gravity of product (ratio of product density compared to density of water; for water $g_s = 1$)
- Metric conversions: $C_v = 1.156(K_v)$
 $1 \text{ bar} = 14.5 \text{ PSI}$
 $1 \text{ m}^3 / \text{hr} = 4.4 \text{ GPM}$

$$C_v = C_{v, \max} f(l)$$

- l is stem position
- $0 \leq l \leq 1$
- closed open

$f(l) = l$
 $f(l) = \sqrt{l}$
 $f(l) = R^{l-1}$

- linear
- square-root (quick opening)
- equal percentage
(R = rangeability coefficient)

The valves in the Control Laboratory have linear inherent characteristics:

$$C_v = C_{v, \max} \cdot l \quad (8)$$

Installed Characteristics

When a valve is installed in a pipeline it becomes part of the flow circuit. Because of the flow resistances of the other components of the flow circuit, the pressure drop across such a valve is no longer constant but varies with the fluid flow rate

The *installed characteristic* of a valve is the flow behaviour when the valve is part of a fluid circuit. For fully turbulent flow through a circuit consisting of a centrifugal pump in series with a control valve and a fixed flow resistance, the installed characteristic of a linear valve is:

$$Q = \frac{l}{\sqrt{(1-\alpha)l^2 + \alpha}} \quad (9)$$

where $Q = q/q_{\max}$ is the fractional flow, and α is relative valve resistance. To describe the flow circuit only one parameter, α , is needed.

Relative Control Valve Resistance

The relative (control) valve resistance is defined as the ratio of the energy dissipated by the valve to the energy dissipated by the system, at maximum flow, i.e.,

$$\alpha = \left[\frac{\text{Energy dissipated by the valve}}{\text{Energy dissipated by the system}} \right]_{\text{maximum flow}} \quad (10)$$

Properly-sized valves have values of α between 1/3 and 2/3 .

Experimental procedure for control valve calibration

1. Select the controller on MANUAL mode and set the manual control input in the software interface so that the valve is completely open.
2. Adjust the water supply hand valve below the rotameter in the water inlet line so that a steady state operation with the maximum level is achieved (this can be achieved for example by setting the inlet flow such that the water flows out the overflow even when the valve is fully open). This guarantees that any effect of changes in liquid height in the tank on flow rate through the control valve is eliminated from the calibration.
3. Determine the range of operation of the valve's output variable (the flow rate of water) that corresponds to the valve's input variable (the signal from the controller, i.e. 0-100%).
4. SET and RECORD the input variable to the valve at a number of points (approximately 10) and MEASURE and RECORD the output variable (flow rate of water through the valve) from the electronic flowmeter

installed on the output line. Cover adequately the range identified in the previous step.

5. To assess the extent of hysteresis perform the calibration process by strictly increasing the signal to the valve and then reverse the process using strictly decreasing signals.
6. Plot the valve characteristics (flow rate versus signal to valve in %) and comment on the results.

Determination of the relative control valve resistance

1. From the calibration curve and practical observations determine whether the valve is a FO or FC valve.
2. Based on the outcome use equation (6) or (7) to calculate the steam positions l .
3. Calculate the fractional flow $Q = q / q_{\max}$.
4. Equation (9) can be rearranged as follows:

$$(Q^{-2} - 1) = \alpha(l^{-2} - 1) \quad (11)$$

Plot $(Q^{-2} - 1)$ versus $(l^{-2} - 1)$. Fit a straight line passing through the origin to the data points. The slope of the straight line gives α . Comment on the value obtained. Properly sized valves have a value between 1/3 and 2/3.

PLEASE NOTE



After Part I and II are completed and before leaving the laboratory, shut-down the rig using the nominal shut-down procedure set out in the appendix.

PART 2 - WEEK 2

III. Experimental procedure for the study of feedback control loop.

The objectives of the exercises are to gain familiarity with feedback control, to appreciate the importance of automatic control and controller tuning, and to gain qualitative appreciation of the effect of each term in a three-term controller on the control performance.

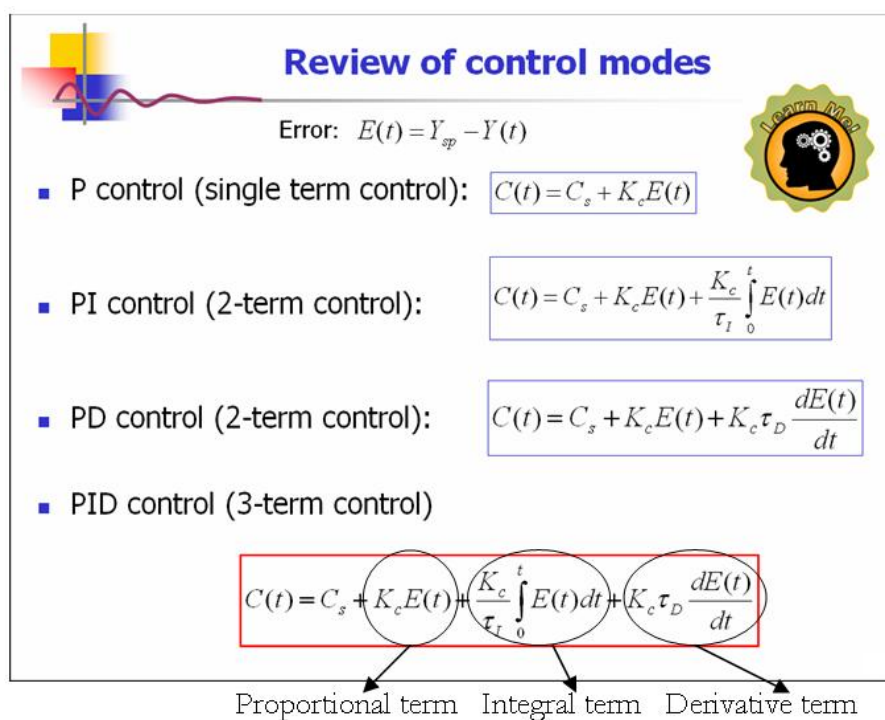
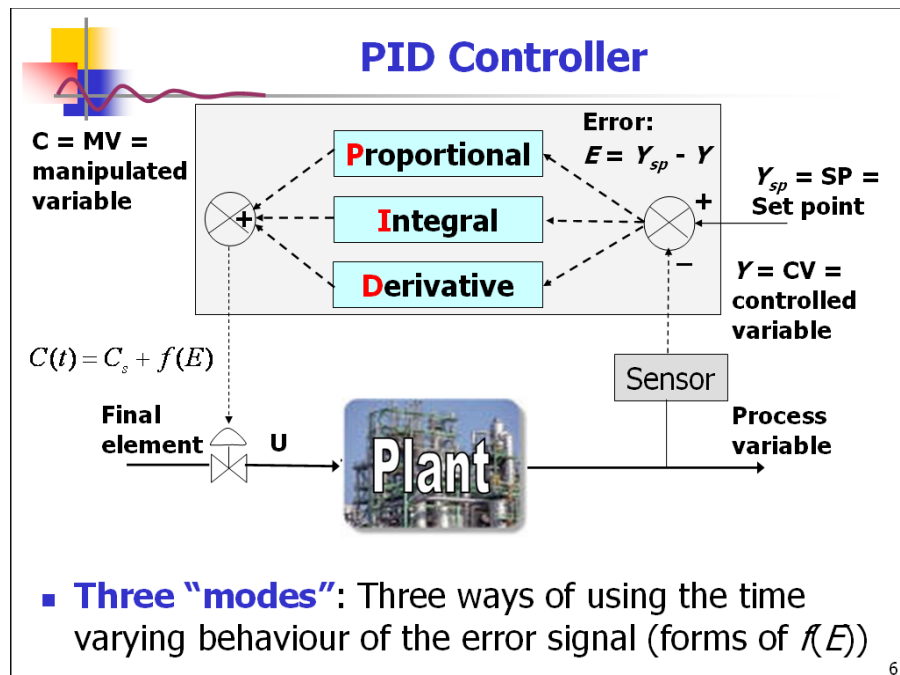
Manual Control

1. With the controller in AUTO mode define a set point (e.g. 50%) and wait until the system stabilizes.
2. Turn the control mode to MANUAL, and change the setpoint (e.g. to 70%).
3. With the manual action buttons in the Process Diagram pane try to bring the level to the new setpoint and maintain it at the new value.
4. Repeat the procedure at a different setpoint.
5. Record the data and analyse the observations. Remember that you can record the measurements in a file by pressing the save button  at the moment when you want the recording to start (e.g. before you change the MANUAL operation mode and change the setpoint). Alternatively (or simultaneously), you can transfer the data to Excel, by pressing the Send to Excel button  after the experiment. You can also record and paste in a Word document the figure plotted by the software by right clicking on the figure widow and selecting “Export Simplified Image” and then paste into a word document. In your report discuss how easy is to maintain the setpoint? This is one of the simplest processes, where you only had to control one single parameter! What is the control error in the case of manual control, i.e. what is the maximum deviation from the setpoint?
6. In the final report present the figures showing the outcome of manual control together with your comments.

Automatic control with heuristic tuning

The most common controller used in the process industries is the so-called three term controller, or PID (proportional-integral-derivative) control. The controller calculates the error between the measured signal and the desired value and changes to manipulated value (valve position) so that the error is decreased. The amount of

change in the manipulated value is a function of the error. This function in the case of PID control has three main components.



The control performance depends strongly on the three parameters of the three term controller:

- Proportional Gain (K_c)

- Integral Time (τ_I)
- Derivative Time (τ_D)

Procedure

1. Set the control mode to AUTO, and wait until the system stabilizes at the desired setpoint value (e.g. 40%).
2. Test the performance of the default control parameters by changing the three controller parameters and comparing how the controller performs in the case of different setpoint changes. Observe how large the overshoot is, how fast the system reaches the new setpoint or whether there is a steady state error, and if there is how large it is. Analyse the form and speed (noise level, oscillations, etc.) of the control action together with the variation of the water level.
3. in the Controller pane of the software, modify one of the three “PID parameters” at a time. Test first the P only control by setting $T_i=0$ and $T_d=0$. Test different gains (minimum 3 different values). Next, fix K_c and vary T_i , but keep $T_d = 0$, and finally fixing K_c and T_i vary T_d .
4. Record the used control parameters and plot the results in your report. Analyse the effect of each term on the control performance.

Automatic tuning

The systematic determination of the controller parameters is called tuning procedure. There are numerous ways to determine the controller parameters based on the criteria considered. The software includes an “Automatic Tuning Wizard” which can help to determine the set of tuning parameters.

1. With the control mode on AUTO, wait until the system stabilizes at the desired level.
2. start the “Automatic Tuning Wizard” from the Controller pane of the window by pressing the “Autotune” button. Follow carefully the procedure. Make sure that you wait enough when the procedure requires to gather information from the system. During the procedure observe that the Autotuning wizard will introduce relay signals in the system to understand its dynamic behaviour. The information is used to determine the control parameters. At the end of the procedure the new parameters will

automatically be saved into the current PID parameters tag in the controller pane and will be used in the system. Test the control performance by changing the setpoint and/or introducing disturbance by changing the input flowrate. Record the controller parameters and the resulted figures.

3. Repeat the autotuning wizard and tests for different controller types. Tune P, PI and PID control structures with Fast, Slow and Normal action. It is not necessary to tune all combinations, select e.g. normal action and tune P, PI, and PID structures, and then with the PI determine the parameters for the fast and slow response.
4. With a fixed set of controller parameters test the control performance for different input flowrates. When the system reaches a stable level increase or decrease the input flow within the physical limits of the controllable system. This will act as a disturbance in the system and the controller will open or close the valve accordingly to bring back the level to its setpoint value. Determine what the maximum input flowrate is, for which the controller is not able to stabilize the system anymore. Explain in your report what the reason is and give an explanation how the maximum input flowrate, for which the controller can stabilize the system relates to the output flowrate from the tank.

Effect of controller sign on system stability

1. With the best set of controller parameters change the sign of the controller gain K_c .
2. Give a setpoint change and observe and RECORD the controller action and system's behaviour.

PLEASE NOTE

After Part I and II are completed and before leaving the laboratory, shut-down the rig using the nominal shut-down procedure set out in the appendix.

APPENDIX A

Nominal Start-up Procedure

1. Turn off all hand valves.
2. Turn on the compressed air at the ball valve on the supply line.
3. Turn on the computer.
4. Turn on the electricity main for the instrumentation.
5. Run the control program.
6. To avoid surges through the glass rotameter, slowly open the water supply hand valve.
7. Set an desired input flow rate. Recommended values:

Rig 1: 0.3 m³/h

Rig 2: 5 l/min

Rig 3: 380 l/h

Rig 4: 3 l/min

Rig 5: 220 l/h

Rig 6: 6 l/min

8. When enough water is in the tank, turn on the outlet pump at the electricity mains.
9. Make sure the controller is in AUTO mode and allow the controller to bring the liquid level to steady state.

Nominal Shut-down Procedure

1. Turn the controller OFF and open the control valve.
2. Turn off the water supply at the hand valve.
3. When the tank is empty, turn off the outlet pump at the electricity mains.
4. Transfer any stored data to a floppy diskette, memory stick, your network drive, or email to yourself.
5. Turn off the computer at the electricity mains.
6. Turn off the instrumentation's power supply at the electricity mains.
7. Turn off the compressed air at the ball valve in the supply line.
8. Place beakers under the drain cocks and drain the system.
9. Close all drain cocks.
10. Make sure that all electrical devices are switched off and that water is not dripping from the mains water supply.

APPENDIX B

Laboratory Report

A group report is required from each team. The body of the report should be no more than 20 pages. You should include key figures, tables and calculations in the main body of the report but you may attach any extra data and peripheral information to appendices, which may be of any size.

Structure and Guidelines for the report:

Summary

Provide a paragraph of the main purpose of the report and a summary of the most important findings.

Table of contents

Introduction (0.5-1 page)

A short introduction related to the importance of understanding process dynamics and control should be provided. The introduction must contain several references. Use appropriate reference style.

Theory (2-5 pages)

Explain in a few sentences the theoretical background related to: (1) how the sensor works, (2) calibration, (3) how the control valve works, (4) PID control. This part should be your own description not copied from the lab manual, with references demonstrating your readings on the topics.

Experimental Procedure (2-4 pages)

Provide a brief summary of the procedure. It is not necessary to copy the procedure from the manual. You should describe briefly the methodology. A proper P&ID of the experimental rig must be provided using standard symbols for instrumentation. It is important that all instruments and elements of your rig are shown in the P&ID.

Results and Discussions (6-10 pages)

Show all results requested in the lab manual. This should contain as a minimum: results from level calibration, analysis of hysteresis, valve calibration, analysis of hysteresis, calculation of the relative control valve resistance, figures and discussion on manual control, results on heuristic tuning, automatic tuning and effect of controller signs. Always compare/contrast and analyse your results, do not only show figures with simple plots. Make sure that the controller tuning parameters are indicated for different parts of the figure and you correlate the dynamic response in your discussion with the changes in the parameters. Main figures should be inserted in the text (always number figures and use figure caption).

Conclusions (0.5 page)

A brief statement with the main results and conclusion of the report.

References

Use proper referencing style and make sure all references are cited in the report.

Appendixes**Marking guidelines****Organization**

Are the report contents structured?

Is a table of contents present?

Are the pages numbered?

Is a summary present?

Are equations numbered?

P&ID

Is the P&ID correct?

Are the manual valves labelled?

Are the symbols correct?

Figures & Graphs

Are the figures and graphs clear?

Is the precision of the data reflected in the graphs?

Is proper analysis and discussion provided?

Are the figures numbered, captions used and referenced properly in the text?

Summary

Does the summary reflect the experimental observations?

Are the numerical values of the principal parameters tabulated?

APPENDIX C

Introduction to the software interface

The software interface allows you to interact with the experimental rig and record all data. The main parts of the interface are shown below. There are three panes with different functionality:

- Process Diagram
- Controller
- Configuration

In the first week you need the functionality of the “Process Diagram” pane only, whereas in the second week you will work with both the “Process Diagram” and the “Controller” panes. The configuration pane should normally not be used during the laboratory exercise.

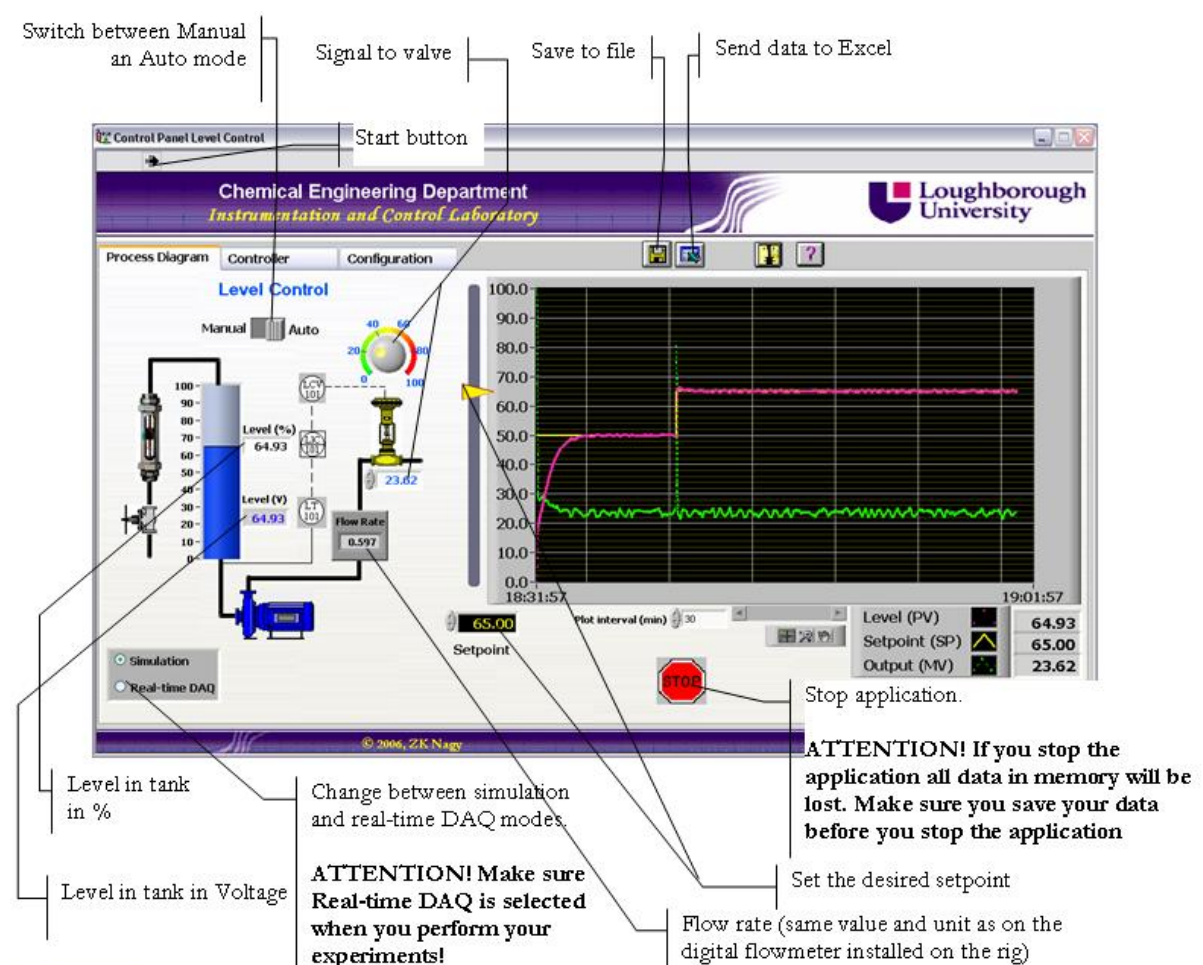


Fig. 2. The “Process Diagram” pane of the laboratory software

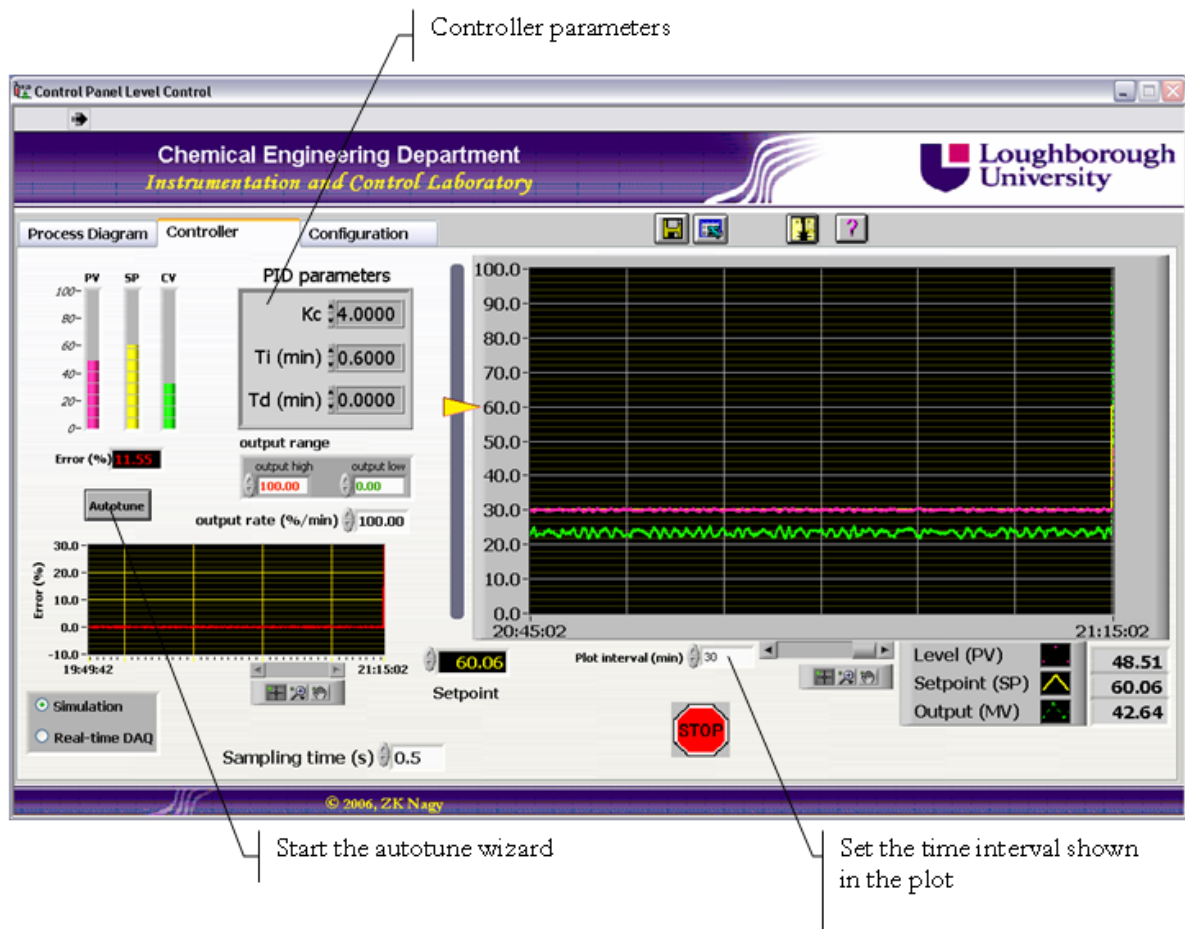




Fig. 3. The “Controller” pane of the laboratory software

Saving your data

Making sure that your data is saved is your responsibility. The software offers several ways to record you data.

1.  - By pressing the save to file button, your data will be saved in a data file, which can be opened by any standard text editor or Excel. Your data will be saved from the moment you pressed the button onward, until you stop the data recording. No data acquired before the moment you activate data recording will be saved in the file. When you activate data recording the software will prompt you for a file name. You can select a file name in your home folder (U drive). The data is recorded at every sampling time. The order of the columns is as follows:

Time (s); Level (%); SP (%); MV (%); FlowRate; Level(V);

2.  - By pressing the “Send to Excel” button, you can send the data from the memory of the software to an Excel workbook. This option works in the opposite way as the Save button. By pressing the button data stored in the memory from the moment you started the software until the moment the button was pressed will be sent to Excel.
3. You can also copy paste snapshots of the plot into your report. However to perform the data analysis you need the values saved with method 1 or 2 above. For the qualitative analysis part or for the appendix it is acceptable however to use the snapshots. This can be obtained by right clicking on the figure widow and selecting “Export Simplified Image...”, then paste it in Word, as shown in the figure below.

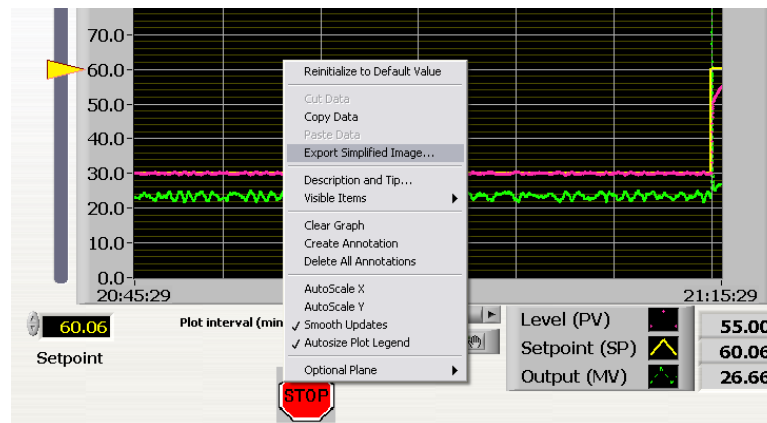


Fig. 4. Exporting snapshots of the plot to other applications

Appendix 3

Second Year Instrumentation and Control Course Survey

This is the survey conducted at the end of the second year course Instrumentation, control and industrial practice in the academic year 2007-2008.

Process Control Lab Questionnaire

Introduction

These questions are proposed for research project purpose aiming at improving the students' laboratory experience; your feedback will help us in this process.

Questions

1. Did you download the virtual (simulated) lab software and used it?

☐No

☐Yes

2. If YES, for how long in average?

.....

3. If YES, have you used it before or after the lab sessions?

☐Before

☐After

☐Both

4. Did you attend the pre lab preparation session?

☐No

☐Yes

5. What is your preference of conducting the Pre-Lab preparation session?

☐Simulated Lab

☐Remote Lab

6. Do you think that simulated lab can replace the real hands-on lab?

☐No

☐Yes

7. Please indicate how much did you find it useful for each of the following components during the Process Control Laboratory?

1= Not useful at all 2= Very little useful 3= A little useful 4= Probably useful
5= Quite useful 6= Very much useful

	1	2	3	4	5	6
The Simulation Lab Software	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
The Lab Pre-Test	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
The Lab Post Test	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
The Pre-Lab Preparation Session	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Doing the Lab experiment in the lecture	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

8. 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?

1= Not at all 2= Very little 3= A little 4=probably 5= Quite
6= Very much

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

9. Did the remote control of the process control test rig in the induction lecture stimulated your interest in the Lab?

☐ No

☐ Yes

☐ Had no effect

10. Do you have any comments for improving the Lab?

11. How much was the Instrumentation and Control Lab motivating for the following points?

1= Not at all 2= Very little 3= A little 4=probably yes 5= Quite
6= Very much

	1	2	3	4	5	6
Continuing an Engineering Career	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Studying Further Control Principles	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Application of Theory into Practice	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Teamwork skills	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Instrumentation awareness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Appendix 4

Pre-Lab Test of Week 1 (2007-2008 & 2008-2009)

This is the instrument that was used to measure the activation of the prehension dimension of Kolb's cycle in relation to Week 1 of the Instrumentation and Control Laboratory session with the second year students.

Student's Name and ID	:	Test start time:
Test rig	:	Test end time:

Pre Lab quizzes for week I:

- 1- Describe the experimentation procedure you are going to follow for the sensor calibration:

- 2- Describe the experimentation procedure you are going to follow for the control valve calibration:

- 3- What is a sensor? Are we using any sensor in the process? How many?
- 4- What is actuator? Are we using any actuator in the process? How many?
- 5- How can we control the output flow rate in the process?
- 6- What do we use for measuring the Inflow rate?
- 7- What do we use for measuring the Outflow rate?

Appendix 5

Pre-Lab Test of Week 2 (2007-2008)

This is the instrument that was used to measure the activation of the prehension dimension of Kolb's cycle in relation to Week 2 of the Instrumentation and Control Laboratory session with the second year students.

Student's Name and ID	:	Test start time:
Test rig	:	Test end time:

Pre Lab quizzes for week II:

- 1- Consider that the process is stabilized on 50% and the control valve manipulator is set to 20; consider that you are controlling the process manually and consider that you changed the set point to 70%:
 - a. How would you control the process to reach the new set point?
 - b. Should the output flow rate increase or decrease? Explain why?
- 2- What does the term "PID" stand for?
- 3- Explain briefly how does the PID controller work on stabilizing the system?

- 4- Consider the process is controlled automatically; consider that the process set point was changed from 50% to 70%. If the PID controller parameters are the following: $K_c=5$, $T_i=0$; $T_d=0$, what is your observation?
- 5- Is it good or not to use PID controller with $T_d \neq 0$, explain your chosen answer clearly.
- 6- Which automatic controlled process is stable (i.e. it can be brought to the given set point)? Explain your answer:
- c. Process controlled with PID controller with the following parameters, $K_c= -4$, $T_i=0.6$, $T_d= 0$.
 - d. Process controlled with PID controller with the following parameters: $K_c= -4$, $T_i=0.7$, $T_d=0$.
- 7- Which controlled process has faster dynamics?
- e. Process controlled with PID controller with the following parameters, $K_c=4$, $T_i=10$, $T_d= 0$.
 - f. Process controlled with PID controller with the following parameters: $K_c=4$, $T_i=0.6$, $T_d=0$.

Appendix 6

Pre-Lab Test of Week 2 (2008-2009)

This is the instrument that was used to measure the activation of the prehension dimension of Kolb's cycle in relation to Week 2 of the Instrumentation and Control Laboratory session with the second year students.

Student's Name and ID	:	Test start time:
Test rig	:	Test end time:

Pre Lab quizzes for week II:

- 1- Consider that the process is stabilized on 50% and the control valve manipulator is set to 20; consider that you are controlling the process manually and consider that you changed the set point to 70%:
 - g. How would you control the process to reach the new set point?
 - h. Should the output flow rate increase or decrease? Explain why?
- 2- What does the term "PID" stand for?
- 3- Explain briefly how does the PID controller work on stabilizing the system?

- 4- Consider the process is controlled automatically; consider that the process set point was changed from 50% to 70%. If the PID controller parameters are the following: $K_c=5$, $T_i=0$; $T_d=0$, what is your observation?
- 5- Which automatic controlled process is stable (i.e. it can be brought to the given set point)? Explain your answer:
- i. Process controlled with PID controller with the following parameters, $K_c= -4$, $T_i=0.6$, $T_d= 0$.
 - j. Process controlled with PID controller with the following parameters: $K_c= -4$, $T_i=0.7$, $T_d=0$.
- 6- Which controlled process has faster dynamics?
- k. Process controlled with PID controller with the following parameters, $K_c=4$, $T_i=10$, $T_d= 0$.
 - l. Process controlled with PID controller with the following parameters: $K_c=4$, $T_i=0.6$, $T_d=0$.

Appendix 7

Post-Lab Test of Week 1 (2007-2008 & 2008-2009)

This is the instrument that was used to measure the activation of the knowledge transformation dimension of Kolb's cycle in relation to Week 1 of the Instrumentation and Control Laboratory session with the second year students.

Student's Name and ID : Test start time:
 Test rig : Test end time:

Post Lab quizzes for week I:

- 1- Have a quick look on the level sensor calibration measurements and draw roughly the level sensor characteristics.



- 2- Have a quick look on the control valve calibration measurements and draw roughly the control valve characteristics.



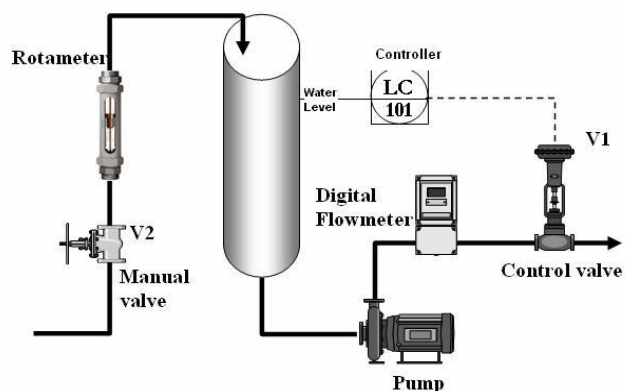
3- What is the zero value of the level sensor?

4- What is a *controller* in your definition?

5- When the process is set to the manual mode, what is the controller?

6- When the process is set to the automatic mode, what is the controller?

7- In the following diagram, is this an open or closed loop process? Why? explain clearly your answers:



Answer:

.....

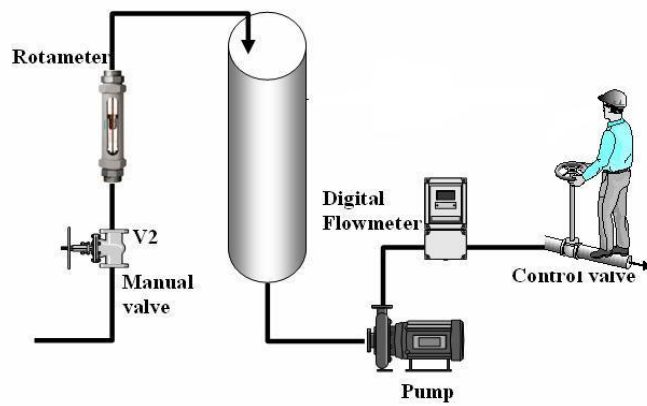
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- 8- In the following diagram, is this an open or closed loop process? Why? explain clearly your answers:



Answer:

.....

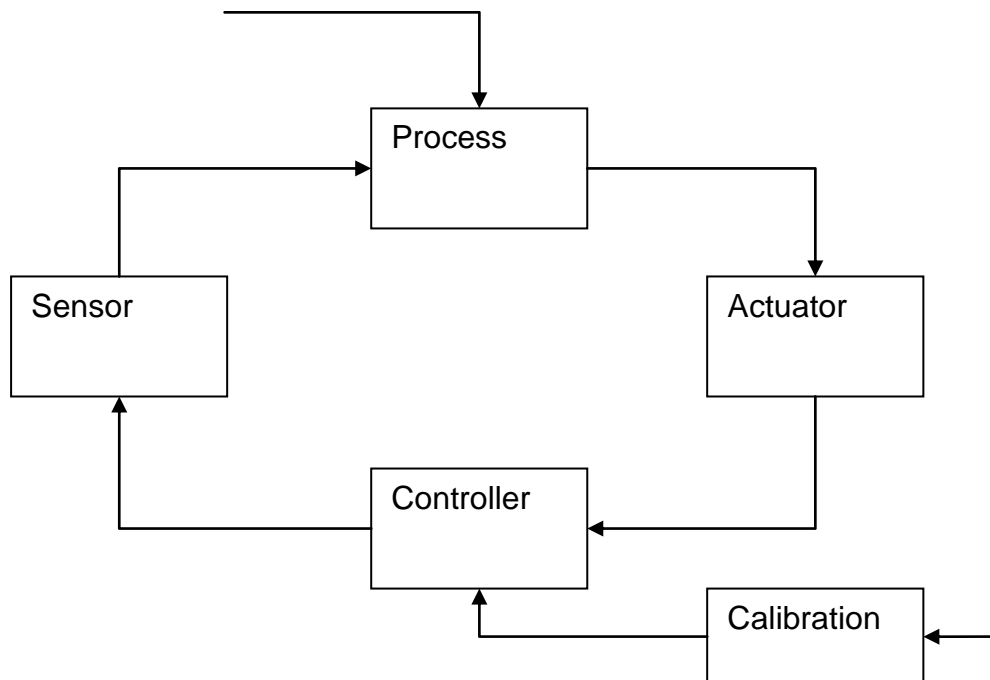
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- 9- Is there anything wrong in the following diagram? If yes, sketch the corrected version? If not explain briefly the process functionality.



- 10- Based on your answer in the previous question, please place the following missing signals in the correct place.

- a- Controller output
- b- Disturbance.
- c- Process output.
- d- Controller input.
- e- Process input.
- f- Desired output value

Appendix 9

Post-Lab Test of Week 2 (2008-2009)

This is the instrument that was used to measure the activation of the knowledge transformation dimension of Kolb's cycle in relation to Week 2 of the Instrumentation and Control Laboratory session with the second year students.

Student's Name and ID	:	Test start time:
Test rig	:	Test end time:

Post Lab quizzes for week II:

- 4- Is it good or not to use PID controller with $T_d \neq 0$, explain your chosen answer clearly.

- 5- As control engineer, you have been asked to make the process dynamic faster given that you can use a **PI** controller, what you will do with the controller parameters to achieve the task?

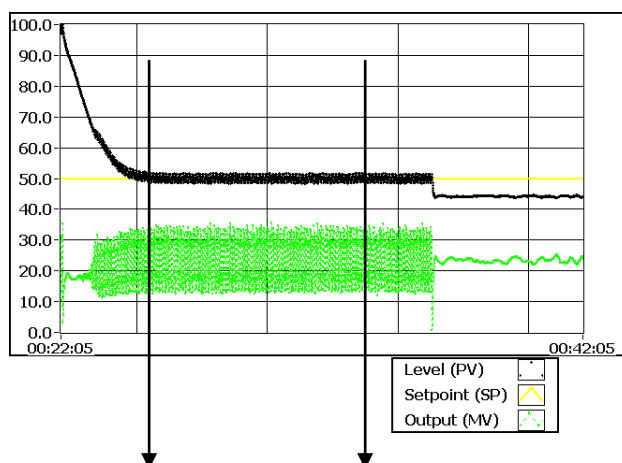
- 6- What is the drawback of using **P** controller only instead of PI or PID controllers? How this can be improved?

- 7- Which one (or more) of the following controller can cause noisy behaviour?
 - a. P
 - b. PI
 - c. PID

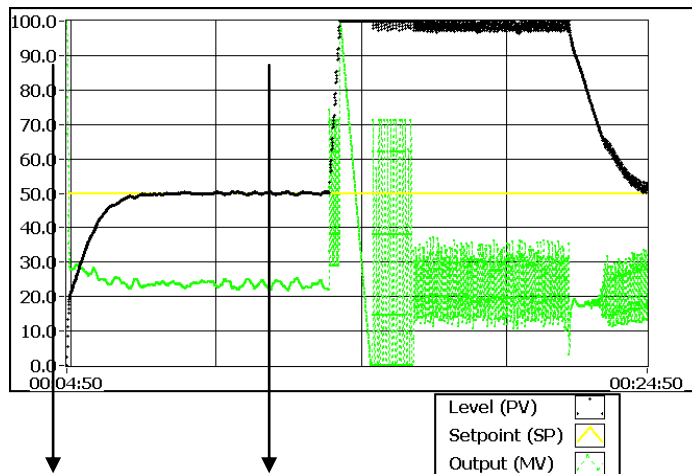
- 8- How feedback is established when automatic control is used?

- 9- What is the best controller in your opinion, P, PI, or PID; rank those from (1 to 3, where 1 is the best) **explain clearly your chosen answer.**

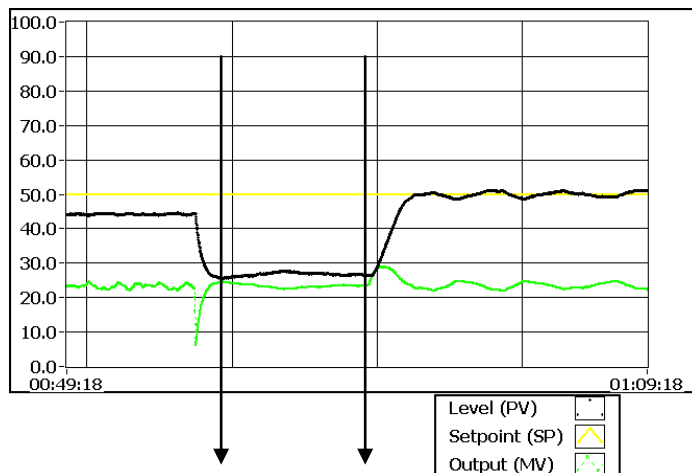
- 10- What is the controller type in between the arrows? Why do you think so?



11- What is the controller type in between the arrows? Why do you think so?



12- What is the controller type in between the arrows? Why do you think so?



13- In the previous figure, what was the used controller before the first arrow? How its parameters differ from the controller used in between the arrows? **Explain why?**

Appendix 10

End of Module Survey for the Course: Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems (MSc 2008)

This is the end of module survey for the course Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems.

Questionnaire

Introduction

These questions are designed for research project aiming at enhancing the students learning, your accurate feedback will help us in this process, please answer all 15 questions, we deeply appreciate your cooperation.

Questions:

1. Do you agree that using the voting system in the lecture have helped you in the following:

1= Strongly disagree
4= Agree a little

2= Disagree
5= Agree

3= Disagree a little
6= Strongly agree

a. In keeping your attention to the lecture?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

b. In understanding theory more?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

c. In highlighting the important parts of the lecture?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

d. In remembering the taught information in the lecture for longer period than the case of classical taught lecture without voting system?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

2. Do you agree with the idea of doing experiments in the classroom for demonstrating the application of theory into practice in other courses?

1= Strongly disagree
4= Agree a little

2= Disagree
5= Agree

3= Disagree a little
6= Strongly agree

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

3. Did Cambridge-MIT remote experiment lecture help you on understanding the theory behind PID control that was exposed in the theoretical lecture?

1= It confused me more
4= Probably yes

2= Did not help at all
5= Quite much helpful

3= A little bit helpful
6= Definitely helpful

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

If it is helpful (choices 3,4,5 or 6), would you please explain us why and how :

.....

.....

.....

.....

.....

4. How would you rate the combination of teaching theory and real experimentation in the classroom (Cambridge-MIT lecture combined with the previously PID control theoretical lecture) in comparison with the purely theoretical lectures that were taught along your MSc program?

1= Much less 2= Less 3= The same 4= More 5=Much more

- a.** The enjoyment factor. ☐₁ ☐₂ ☐₃ ☐₄ ☐₅
- b.** The conceptual understanding ☐₁ ☐₂ ☐₃ ☐₄ ☐₅
- c.** The motivating role towards
an engineering career. ☐₁ ☐₂ ☐₃ ☐₄ ☐₅
- d.** Studying more theory about the
presented material. ☐₁ ☐₂ ☐₃ ☐₄ ☐₅

5. Which rank would you rank this module in comparison with the rest of taught modules in your MSc?

1st ☐

2nd ☐

3rd ☐

4th ☐

5th ☐

6th ☐

Would you please explain us why did you choose this answer?

.....

.....

.....

.....

.....

6. What was the best thing in this module? And what was the worst thing?

The Best

.....

.....

The Worst

.....

.....

7. In an engineering plant, do you think that performing remote control, maintenance, or monitoring of real industrial plant located far from your physical location through the Internet is achievable?

1= Not at all

4= Probably yes

2= Very little achievable

5= Quite achievable

3= A little achievable

6= Definitely achievable

1 ☐

2 ☐

3 ☐

4 ☐

5 ☐

6 ☐

Appendix 11

End of Module Survey for the Course: Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems (MSc 2009)

This is the end of module survey for the course Advanced Computational Methods for Modelling and Analysis of Chemical Engineering Systems.

Questionnaire

Introduction

These questions are designed for research project aiming at enhancing the students learning, your accurate feedback will help us in this process, please answer all 15 questions, we deeply appreciate your cooperation.

Questions:

1. Do you agree that using the voting system in the lecture have helped you in the following:

1= Strongly disagree
4= Agree a little

2= Disagree
5= Agree

3= Disagree a little
6= Strongly agree

a. In keeping your attention to the lecture?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

b. In understanding theory more?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

c. In highlighting the important parts of the lecture?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

d. In remembering the taught information in the lecture for longer period than the case of classical taught lecture without voting system?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

2. Do you agree with the idea of doing experiments in the classroom for demonstrating the application of theory into practice in other courses?

1= Strongly disagree
4= Agree a little

2= Disagree
5= Agree

3= Disagree a little
6= Strongly agree

1 ☐

2 ☐

3 ☐

4 ☐

5 ☐

6 ☐

3. Did the remote experiment lecture help you on understanding the theory behind PID control that was exposed in the theoretical lecture?

1= It confused me more

2= Did not help at all

3= A little bit helpful

4= Probably yes

5= Quite much helpful

6= Definitely helpful

1 ☐

2 ☐

3 ☐

4 ☐

5 ☐

6 ☐

If it is helpful (choices 3,4,5 or 6), would you please explain us why and how :

.....

.....

.....

.....

.....

4. How would you rate the combination of teaching theory and real experimentation in the classroom (remote lab lecture combined with the previously PID control theoretical lecture) in comparison with the purely theoretical lectures that were taught along your MSc program?

1= Much less 2= Less 3= The same 4= More 5= Much more

a. The enjoyment factor.

☐₁

☐₂

☐₃

☐₄

☐₅

b. The conceptual understanding

☐₁

☐₂

☐₃

☐₄

☐₅

c. The motivating role towards
an engineering career.

☐₁

☐₂

☐₃

☐₄

☐₅

d. Studying more theory about the
presented material.

☐₁

☐₂

☐₃

☐₄

☐₅

5. If you attended the post lab activity session on Thursday 5.06.2009, please answer this question. To which extent was the post lab activity session was helpful in understanding more what you have learnt during the hands-on lab session that took place one week earlier?

1= It confused me more
4= Probably yes

2= Did not help at all
5= Quite much helpful

3= A little bit helpful
6= Definitely helpful

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

6. The post lab activity was conducted using the virtual lab. To which extent you think it should be done through the remote lab instead of the virtual lab?

1= Strongly disagree
4= Agree a little

2= Disagree
5= Agree

3= Disagree a little
6= Strongly agree

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

7. How much would you rate the laboratory experience importance as a part of this module?

1= Strongly disagree
4= Agree a little

2= Disagree
5= Agree

3= Disagree a little
6= Strongly agree

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

8. Do you like that laboratory to be a core part of other MSc modules that does not offer labs?

1= Strongly disagree
4= Agree a little

2= Disagree
5= Agree

3= Disagree a little
6= Strongly agree

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

If you agree (4,5,6). Please explain why Laboratory is important for you:

.....

.....

.....

.....

.....

.....

.....

9. Which rank would you rank this module in comparison with the rest of taught modules in your MSc?

1st ☐ 2nd ☐ 3rd ☐ 4th ☐ 5th ☐ 6th ☐

Would you please explain us why did you choose this answer?

.....

.....

.....

.....

.....

10. What was the best thing in this module? And what was the worst thing?

The Best.....

.....

.....

The Worst

.....

.....

11. In an engineering plant, do you think that performing remote control, maintenance, or monitoring of real industrial plant located far from your physical location through the Internet is achievable?

1= Not at all 2= Very little achievable 3= A little achievable
4= Probably yes 5= Quite achievable 6= Definitely achievable

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐

Appendix 12

LabVIEW Programming

This appendix provides an executive summary of LabVIEW programming environment and descriptions of some parts of the LabVIEW code of the developed TriLab software given in Chapter 5.

The LabVIEW Programming Environment

The LabVIEW developing environment comprises three main parts: the front panel, the block diagram and the icon/connector. The front panel is the interactive GUI of a VI, named so since it is similar to a physical instrument's front panel. On the front panels, controls (user inputs variables) as well as indicators (the LabVIEW programme outputs) are placed. The controls generally look similar to the physical buttons, switches and knobs that can be found on a conventional instrument. Controls supply the block diagram with the needed data for processing. The indicators receive back the generated data by the LabVIEW programme and display them for the user.

The block diagram is the place where the actual VI's source code (developed in G) is contained; hence, the block diagram is similar to the text lines found in conventional programming languages such as Java or C++. The components of the block diagram (the G-code) are lower level VIs, built-in functions, constants and program execution control structures such as 'For' and 'While' loops. When the programmer places a control or indicator on the front panel, LabVIEW will automatically create a relevant 'terminal' on the block diagram.

Similar to most programming languages, LabVIEW use *For* and *While* loops to control repetitive operations in a VI. The LabVIEW *For* and *While* loops are resizable boxes in which the sub-routine that the programmer needs to be repeated is placed. The *For* loop executes for a specific number of times. The *While* loop includes a *conditional terminal* that can terminate the loop execution. Transferring a variable value from one iteration to the next of a *For* or *While* loop in LabVIEW is achieved through a so-called *shift register*. The conventional programming command '*if-then-else*' is achieved in LabVIEW through a *case structure*. Case structures have multiple sub-diagrams, but only one is executed at once. The selection of this sub diagram depends on the condition status.

LabVIEW also contains *dialog* functions which bring up a dialog box containing a message to the user. Procedural programming languages like C or Java have inherent control flow because statements execute in the order they are written in the program, but LabVIEW G-Code executes at once, hence providing easily parallel computation features. LabVIEW can determine the sequence of program execution (control flow) by using *Sequence Structure*, which is an ordered set of frames that execute sequentially. LabVIEW contains several timing functions such as *Wait(ms)*, *Tick Count(ms)*, *Wait Until Next ms Multiple*, *Time Delay* and *Elapsed Time* to help to measure time, synchronise tasks and allow enough idle processor time.

LabVIEW, like other programming languages, can process scalar variables and arrays of variables. A LabVIEW array is a collection of elements that are all of the same nature. There are many built-in functions in LabVIEW for manipulating arrays such as *Initialise Array*, *Array Size*, *Build Array*, *Array Subset*, *Delete From Array* etc. For grouping elements of a different nature, LabVIEW uses the data type *cluster*, which is analogous to a *struct* in C or the data member of a *class* in C# or Java. A LabVIEW *cluster* can be thought of as a bundle of different wires in one cable. Clusters are particularly useful for reducing the number of wires or terminals associated with a VI. Many LabVIEW functions are *polymorphic*, i.e. can adjust to inputs of data of different sizes.

Visual representation of data in LabVIEW can be achieved by using *Chart* and *Graph*. A *chart* appends new data to old data and plots one point (or set of points) at a time (added to the previous points) hence showing the data change in a dynamic way. A *graph* shows the full set of data after it has been generated. A *waveform* is a useful LabVIEW function for plotting analogue signals against time. LabVIEW also offers the possibility of 3D plots, but this is only available on Windows machines.

LabVIEW includes several functions for manipulating strings such as obtaining the string length, merging two strings together, converting a string to a number etc. With the LabVIEW functions *Write to Spreadsheet File* and *Read From Spreadsheet File*, a programmer is able to write and read data to and from a file. For dealing with dynamic data, the functions *Write to Measurement File* and *Read From Measurement File* are useful.

Similar to C, Java or Pascal, LabVIEW holds *Local*, *Global* and *Shared Variables*. The local variable enables a front panel object to be accessed from different places in the block diagram of a VI reducing the wiring and the graphical complexity of the block diagram. A global variable enables values of any data

type to be accessed by many VIs that are running at the same time while local variables are limited to the same VI only. A shared variable is similar to a global variable but works across multiple local and networked applications. Every indicator and control in LabVIEW has a set of base properties such as colour, visibility etc. These properties can be programmatically manipulated with the LabVIEW function *Property Node*.

The G- Programming of the Armfield LabVIEW Software

In this section, a demonstration of the most important units of the Armfield LabVIEW software is presented. Sample G-codes are shown with a brief description.

The Armfield LabVIEW Driver

To conduct the real experiment, a special interfacing arrangement with LabVIEW must be achieved. The LabVIEW interfacing will normally consist of interfacing data acquisition hardware (DAQ) and a corresponding LabVIEW code to be implemented as an additional component of the LabVIEW software.

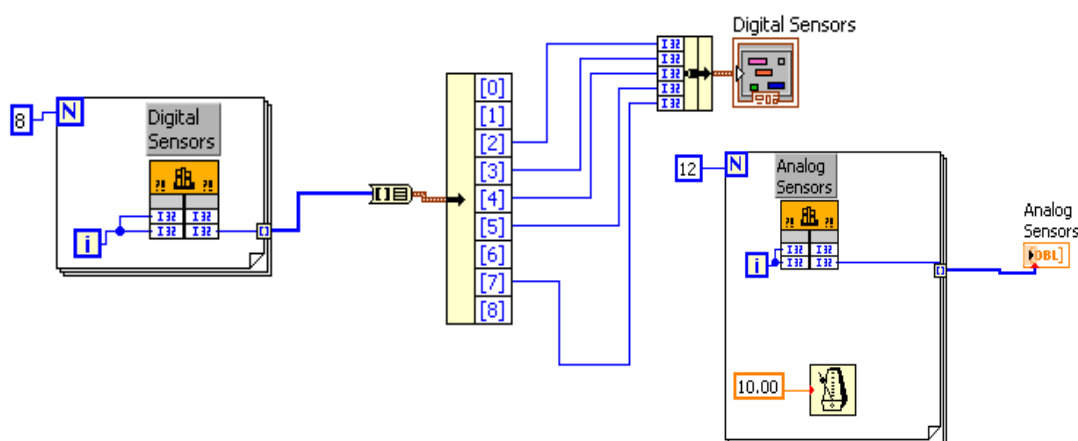


Figure A.1. The G-code of the Armfield sensors driver for analogue and digital inputs.

The rig comes with a DLL driver file that can be read in LabVIEW through 'Call library function'. There are analogue and digital sensors in the rig as well as analogue and digital actuators. The process analogue sensors are: four temperature sensors, three pressure sensors, level sensor, flow sensor, conductivity sensor and pH sensor. The digital sensors are: hot water level sensor, over temperature of hot water sensor, differential level switch on/off sensor, level switch on/off. The analogue outputs are: hot water pump, PSV pump (the proportional pump), pumps A and B (the two non-dedicated pumps). The digital outputs are: thermostat, stirrer and three solenoid pumps.

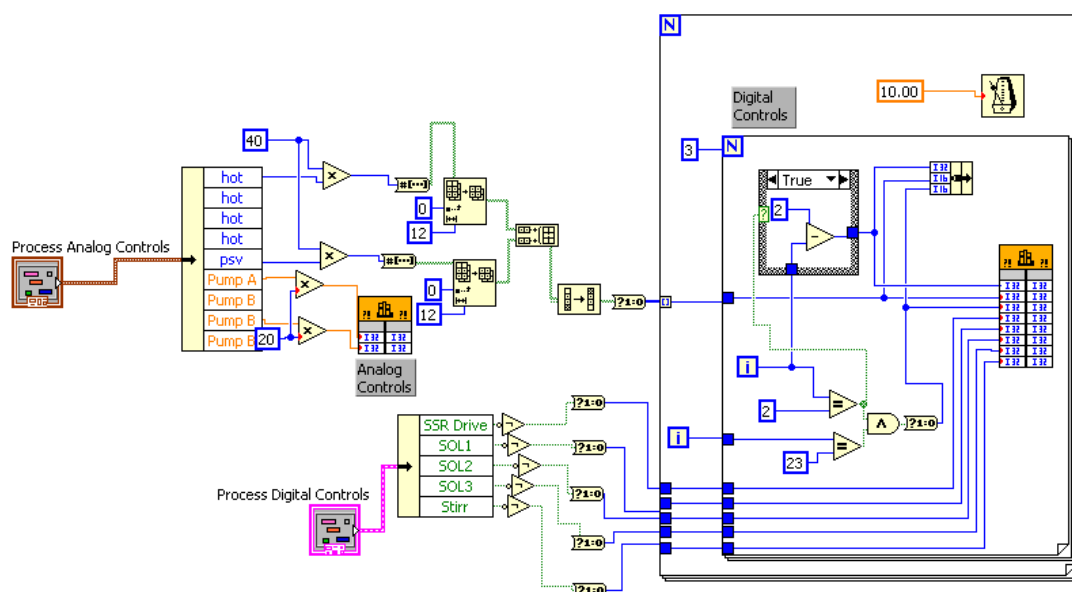


Figure A.2. The G-code of the Armfield controls (digital and analogue outputs).

All of these can be read or written to through the mentioned function in a straightforward way except the hot water and the PSV pumps. These are controlled through an electronic chip that requires special coding to deliver the needed input. The coding has been implemented in LabVIEW, and a generic LabVIEW driver for the Armfield rig has been developed. The driver provides an access to all digital and analogue inputs and outputs. The G-code of the Armfield LabVIEW driver for reading the process variables is shown in Figure A.1.

The G-code for writing to the process analogue and digital controls variables is shown in Figure A.2. For portability issues, it is recommended to frame an independent piece of code such as the Armfield LabVIEW driver in an independent container which is done in LabVIEW through the sub VI possibility. The driver G-code has been saved as a sub VI with three main inputs (cluster of process analogue inputs, process digital inputs and configuration parameters) and two main outputs (cluster of analogue sensors and digital sensors).

Part of the Core G-Code of the Lab Process

As shown before, the user has the following possibilities to choose from:

- Simulation or real experimentation.
- Inflow or outflow control.

This hierarchy is implemented in LabVIEW through two cascaded case structures, cases one and two in Figure A.3. Case one is controlled through the 'Radio Buttons' which contains three possibilities:

- Level Control (Sim): here the level control process is run with a simulation model.
- Level Control (DAQ): here the level control process is real and variables communication with the Armfield is established through the Armfield driver.
- Whole Plant (DAQ): here all the Armfield rig inputs and outputs can be manipulated through the driver.

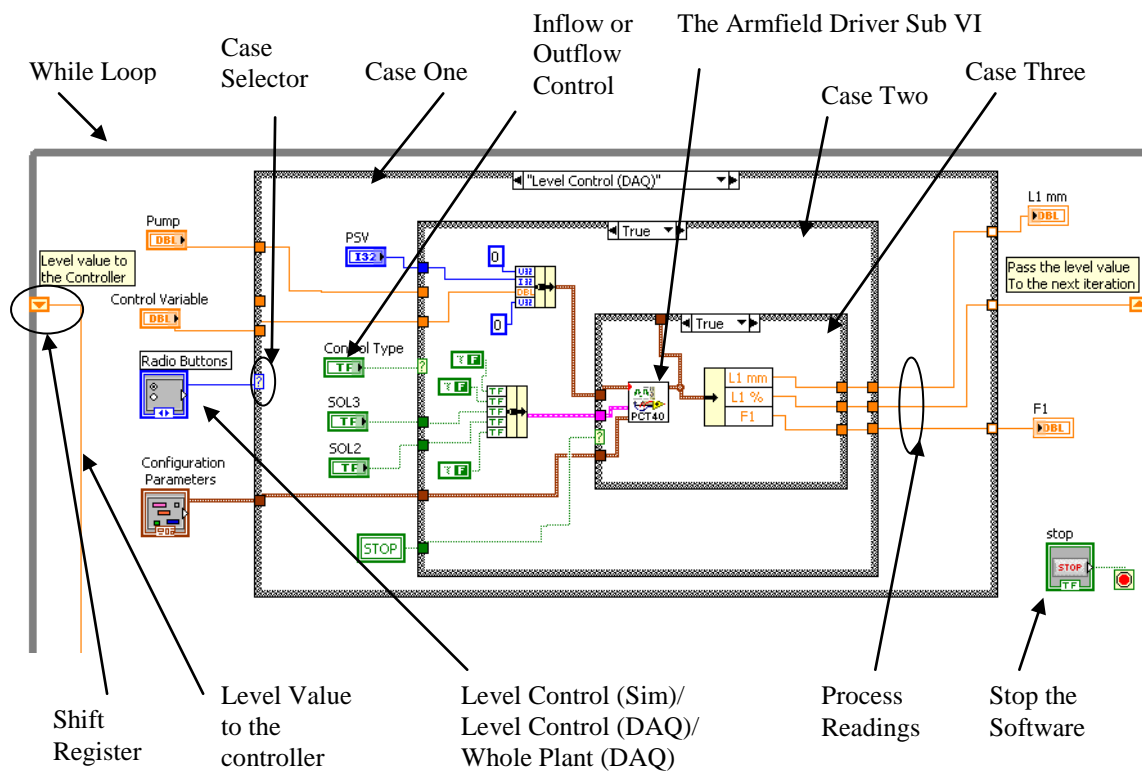


Figure A.3. Some of the main G-code of the Armfield level process.

Hence, case one holds three cases. Case two holds two cases, true and false, and is manipulated by the 'Control Type' button. The true case refers to the outflow control case where the level in the Armfield process tank is controlled via the outflow pump, while the false case refers to the case where the level is controlled via the inflow pump (PSV). The third case is controlled via the 'Stop' button and holds true and false cases. The true refers to normal operation of the software when input and output values are read from the driver according to the

corresponding case values of the case structures one and two. When the user ends the software operation, the case structure three switches to the false case and zero values are written to the driver inputs to ensure that all the rig actuators are switched off.

Part of the G-Code of the Controller

National Instruments provides a supporting add-on toolkit to LabVIEW to implement control applications, the PID control toolkit. The toolkit provides PID VIs that can be used with data acquisition hardware to develop LabVIEW-based control applications. The VIs of the toolkit cover PID control, Gain-Scheduled PID, PID autotuning, Error-squared PID, Lead-Lag compensation, Setpoint profile generation, Multi-loop cascade control, Feedforward control, Override control, Ratio/bias control and fuzzy logic-based control. All VIs can be modified by the control application programmer. Two main VIs from the PID control toolkit were used implement the level control experiment, the *PID advanced* and the *PID Autotuning*. A third VI, *PID Control Input Filter*, was used to filter the control signal. The *PID advanced* VI, shown in Figure A.4, takes many inputs that include adjusting the VI to function in automatic mode or in manual mode, the manual control signal, the control signal range, the setpoint, the process variable the user wants to control, the setpoint range and the PID controller parameters etc. The default setpoint range is 0 to 100, which corresponds to values specified in terms

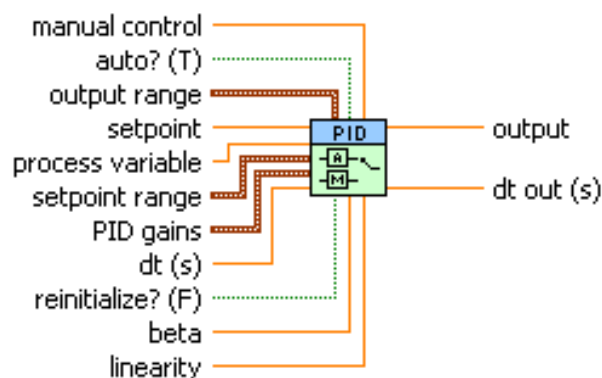


Figure A.4. The PID advanced VI of the LabVIEW PID Toolkit

of percentage of full scale; however, the programmer can change this range to a different one if needed. The value *beta* specifies the relative emphasis of disturbance rejection to setpoint tracking; the default value 1 corresponds to most applications. The *linearity* value sets linearity of the error response with a range from 0 to 1.0; the value 1 corresponds to normal linear response. The *PID*

advanced VI is associated with the word ‘advanced’ because it uses more complicated algorithms to calculate the error and the controller actions. The error is calculated as follows:

$$E(k) = (SP(k) - Y(k))(L + (1 - L) \times \frac{|SP(k) - Y(k)|}{SP_{range}})$$

Where L is the linearity value and SP_{range} defines the setpoint range. In the case of proportional controller, the error is calculated as follows:

$$Eb(k) = (\beta \times SP(k) - Y(k))(L + (1 - L) \times \frac{|\beta \times SP(k) - Y(k)|}{SP_{range}})$$

where β specifies the relative emphasis of disturbance rejection. When β is set to less than one, it reduces the setpoint response overshoot without affecting the load-disturbance response. A PID controller with adjusted β is referred to as a two degree of freedom PID algorithm. The proportional action is then given by:

$$u_p(k) = K_p \times Eb(k)$$

An advanced trapezoidal integration formula is used to calculate the integration action with reduced sharp changes when sudden change in the setpoint of the process output takes place. The integration formula includes a nonlinear adjustment element that counteracts overshoots when they occur. The advanced integration formula is given by:

$$u_i(k) = \frac{K_p}{T_i} \sum_{i=1}^k \left[\frac{E(i) - E(i-1)}{2} \right] h \left[\frac{1}{1 + \frac{10 \times E^2(i)}{SP_{range}^2}} \right]$$

The output of the *PID advanced* VI is the control signal which can be manually or automatically generated according to the VI's input configuration.

The *PID autotuning* VI includes many inputs for passing some similar values to the *PID advanced* and values needed for the autotuning process such as the autotuning parameters and an input for triggering the autotuning process. The *PID autotuning* VI architecture consists of three main components, the relay signal generation, the autotuning wizard and the PID controller. The latter is the same *PID advanced* VI, hence the *PID autotuning* VI was modified to include all the *PID advanced* inputs. With the new VI, the programmer can use one component for producing a PID control application. When the input *autotune* is

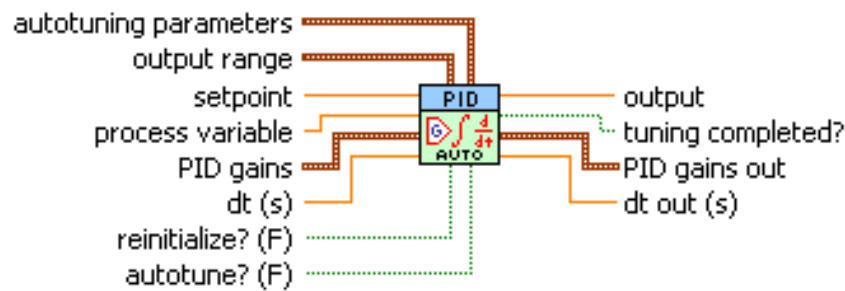


Figure A.5. The PID autotuning VI of the LabVIEW PID Toolkit.

set to false, the VI works as *PID advanced*. When the input *autotune* is set to true, the autotuning process starts and the autotuning wizard appears as shown in Figure A.7. There are four main autotuning parameters that define the controller type (P, PI, or PID), the number of relay cycles used for the autotuning process, the relay amplitude and the controller design nature, whether slow, normal or fast. Once the user has defined these parameters, the autotuning wizard proceeds towards the next steps where the noise is estimated and the relay is applied, and finally the new set of parameters will be displayed and saved to the controller parameters under the user prompt. It is essential to stabilise the process before starting the autotuning process. Figure A.6. shows a modified autotuning VI.

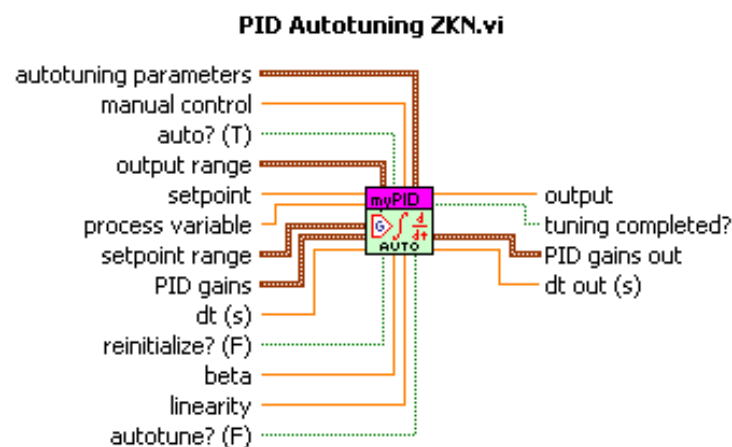


Figure A.6. The modified PID autotuning VI.

The autotuning VI reads the *Auto* signal; if true, then the VI will regulate the process automatically using the embedded *PID advanced* VI; if false, the process is controlled manually by the user and the control signal is delivered either

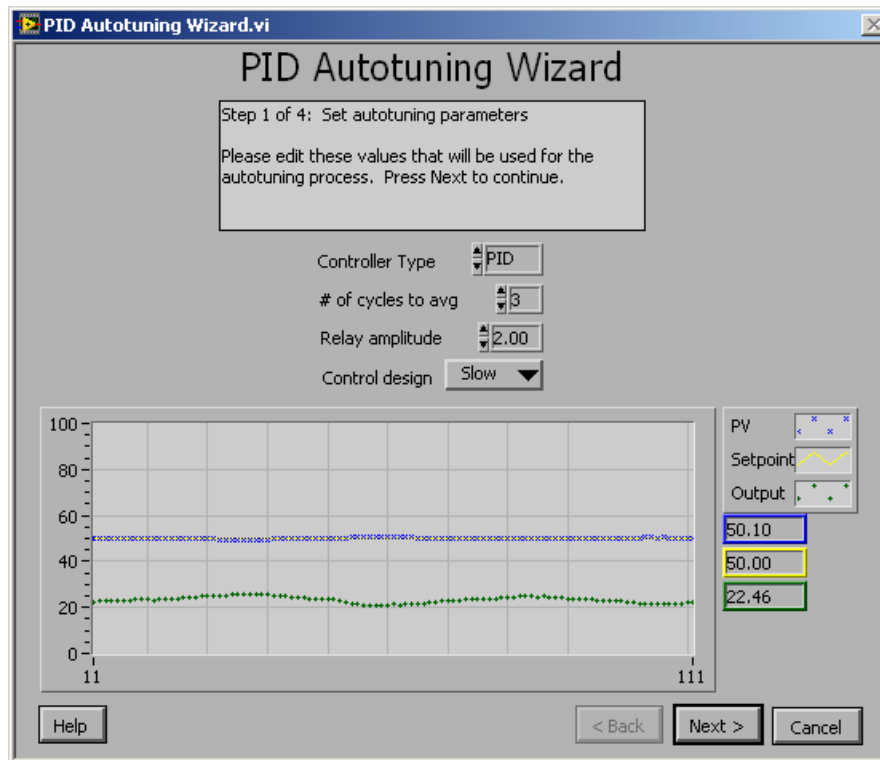


Figure A.7. Configuration window of the PID autotuning VI.

through the *pump* or the *PSV* controls. The manual control, either pump or PSV, is determined through the case structures set 1. When the outer case is false, this means manual control is selected. Then the inner case determines whether a pump or PSV value passes as a manual control signal. This is determined by the *control type* control. When the latter is true, the case includes the *pump*, while the *PSV* would appear in the false case. Many local variables such as PSV, pump and control type were used in the G-code to minimise the wiring and enhance the code readability.

When the *Auto* signal is true, the autotuning VI is activated to work as an automatic PID controller; the regulated output is then passed from the autotuning VI to the *PID control input filter* VI to filter the signal. The filtered signal is then written either to the *pump* or to the *PSV*. This is determined by the case structures set two. When the *autotune?* signal is true, the autotuning procedure is activated. Once it is finished, the tuned set is written to the *PID parameters* variable (see Figure A.8).

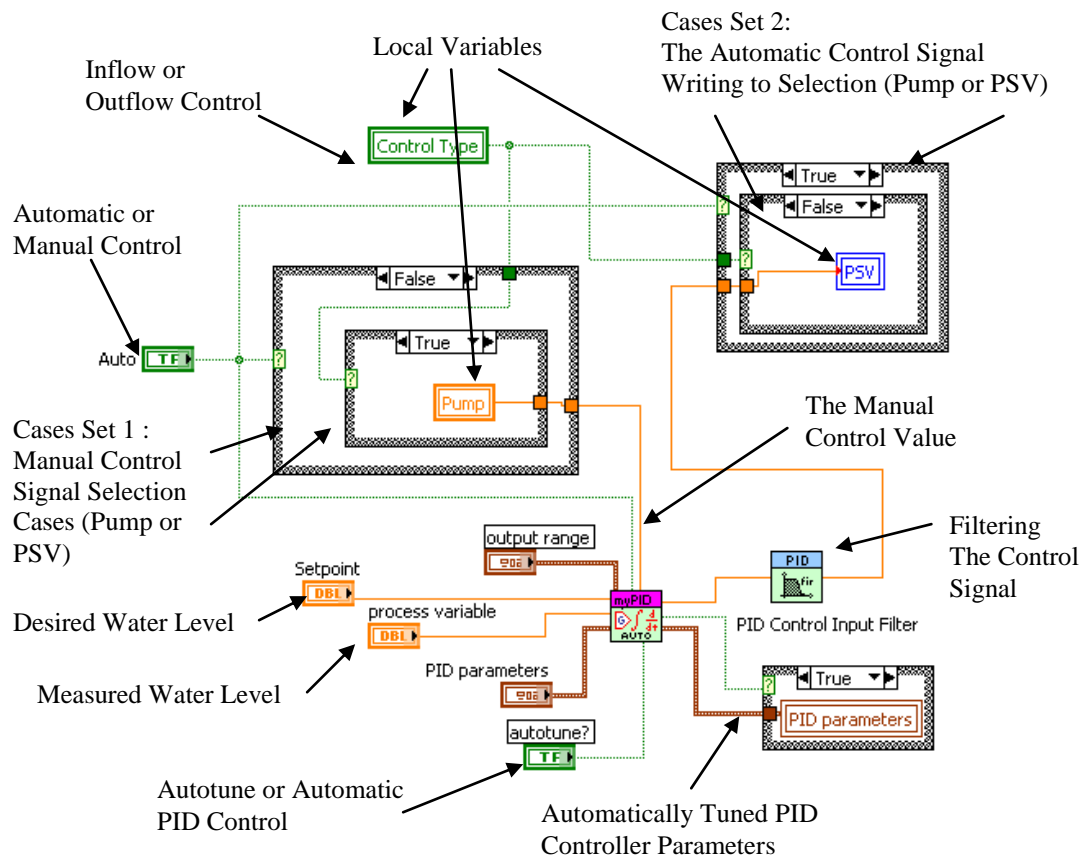


Figure A.8. Autotune or automatic PID control.

Appendix 13

Joomla Technical Requirements

This appendix provides an overview of the technical requirements of installing the Joomla web content management system.

Joomla Technical Requirement

Joomla is a dynamic web content management system; hence, it requires a number of web applications to work properly. These are the 'Apache HTTP Server' web server, the dynamic scripting language 'PHP' and the database management system 'MySQL', which must be installed on the web server.

Apache HTTP Server: The Apache HTTP server is open source software developed for offering a free tool to implement HTTP-based web servers. Apache holds an active volunteering community from around the world which works continuously to enhance the code, develop relevant documentation, and release new versions. Apache supports a number of operating systems: Unix, Linux and Windows.

PHP Hypertext Preprocessor: Is a server-side programming language used mainly for programming dynamic web pages. It was created by Rasmus Lerdorf in 1995 as a package he called 'Personal Home Page Tool', hence the name PHP. The PHP is an open source technology and is supported by a large community of developers worldwide. PHP is available for free. PHP is platform independent and can support many database systems including MySQL.

MySQL: Is a scalable relational database management system developed by Michael Widenius in 1994. Like PHP and Apache, MySQL is also a free and open source tool which can execute on many platforms. A database management system such as MySQL provides mechanisms for storing, organizing, retrieving and modifying data from a database. Figure A.9 shows Joomla's dependency on the previous required technologies. The diagram shows how Joomla works on the top of three other levels of technology.

When Joomla is to be installed on a local host, the previous three applications should be installed first. First the Apache web server, PHP and MySQL should be installed, a database should be created and then Joomla is installed. They can be

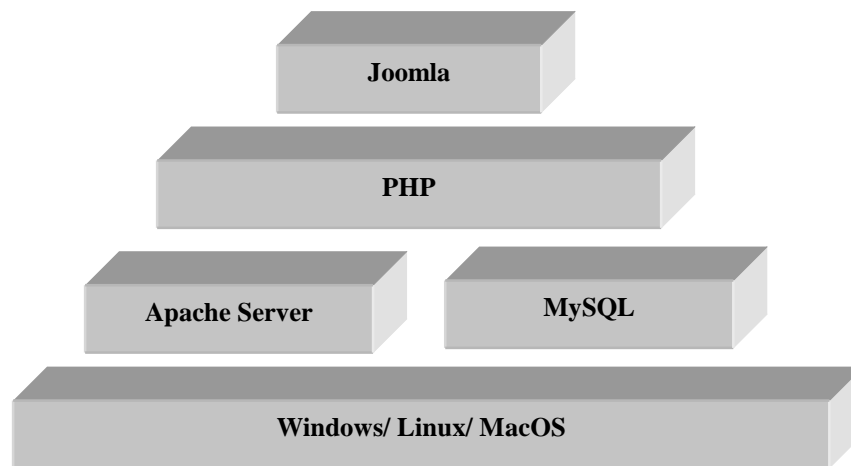



Figure A.9. Joomla dependency on web applications.

installed and configured individually or can be installed as a group included in a preconfigured web applications package such as WAMP, MAMP, LAMP or XAMPP, the second option being the most recommended. In the case of installing Joomla on a remote host that is reserved on a hosting company server, the needed software applications for Joomla should normally be installed.

Appendix 14

In-Classroom Quiz of PID Control

This quiz has been used with the students of the second year course Instrumentation, Control and Industrial Practice in 2008-2009 academic year.



Which of the following is a closed loop control system?

1. Input → Process → Output Sensor
2. Input → Controller → Process → Output Sensor
3. Input → Controller → Process → Output Sensor → Comparison → Controller
4. Input → Controller → Actuator → Process → Output Sensor → Comparison → Controller
5. Input → Controller → Actuator → Process → Output Sensor → Comparison → Actuator
6. None of the Above !
7. I don't know !

0%	0%	0%	0%	0%	0%	0%
1	2	3	4	5	6	7

Calculate and answer !

Given $C_s = 0$, $K_c = 1$, $\tau_i = 1$, $\tau_d = 1$, $E(t) = 2t$, $t = 1$ sec,
Calculate the Control Signal of a PID Controller
How much is it?

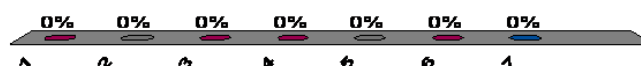
1. 3
2. 4
3. 5
4. 6
5. 7
6. Non of the above
7. I don't know



Calculate and answer !

Given $C_s = 0$, $K_c = 2$, $\tau_i = 2$, $\tau_d = 1$, $E(t) = 2t$, $t = 1$ sec,
Calculate the Control Signal of a PI Controller
How much is it?

1. 3
2. 4
3. 5
4. 6
5. 7
6. Non of the above
7. I don't know



Calculate and answer !

Given $C_s = 0$, $K_c = 2$, $\tau_i = 2$, $\tau_d = 1$, $E(t) = 2t$, $t = 1$ sec,

Calculate the Control Signal of a PD Controller

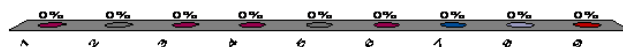
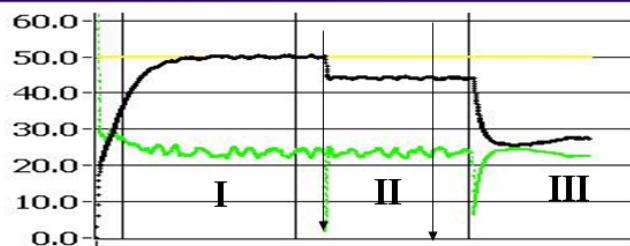
How much is it?

1. 3
2. 4
3. 5
4. 6
5. 7
6. Non of the above
7. I don't know



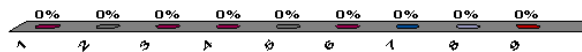
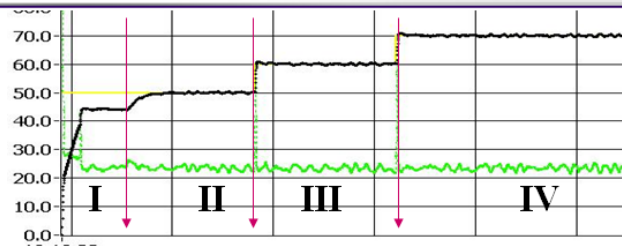
What Sequence of Controllers have been used (I,II,III)?

1. PID, PI, PI
2. PI, PD, P
3. PI, P, P (higher K_c)
4. PI, P, PD
5. PID, P, P (lower K_c)
6. PI, P, P (lower K_c)
7. PD, P, P (higher K_c)
8. None of the above
9. I don't know



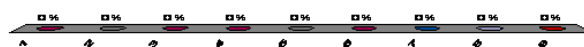
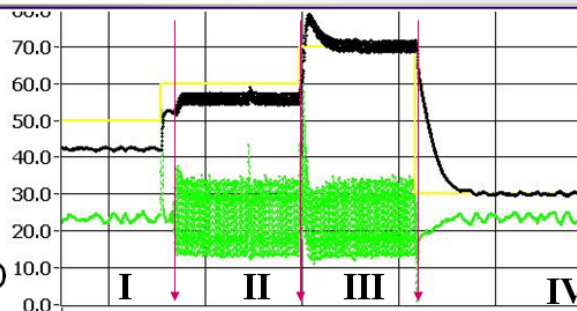
What Sequence of Controllers have been used (I,II,III, IV)?

1. PD, PID, PID, PID
2. P, PI, PID, PID
3. P, PD, PD, PD
4. P, PI, PID, P (lower K_c)
5. P, PI, PI, PI
6. P, PD, PD, PD
7. PD, PI, PI, PI
8. Non of the above!
9. I don't know!



What Sequence of Controllers have been used (I,II,III, IV)?

1. PD, PI, PID, P
2. P, PI, PD, PID
3. PD, P, PI, PID
4. P, PD, PD (K_c higher), PID
5. P, PD, PID, PI
6. P, P(K_c lower), PID, PI
7. P, PD, PID, PID (T_d higher)
8. None of the above
9. I don't know !



Publications

Journal Articles:

1. Abdulwahed M., & Nagy Z. K. (2009) Applying Kolb's experiential learning on laboratory education, case study. *Journal of Engineering Education*, 98(3), 283-294.
2. Abdulwahed M., Nagy Z. K. & Blanchard R. E. (2009) Constructivist project based learning design, a cybernetics approach. *Journal of Education, Information and Cybernetics*, 1(2), 1-8.

Workshop:

3. Nagy Z. K., Abdulwahed M., Blanchard R. E., Lindsay E., and Read L., (2008) The impact of remote and virtual laboratories in engineering education. In *Proceedings of the international conference on innovation, good practice and research in engineering education, EE2008, Engineering Subject Centre, Loughborough, UK, 14-16 July*.

Refereed Conference Papers:

4. Abdulwahed, M., & Nagy Z. K. (2009) Sharing a process control experimental rig online. In *Proceedings of the Twentieth Annual Conference of the Australian Association for Engineering Education, Adelaide, Australia 6-9 December*.
5. Abdulwahed M., Nagy Z. K., & Blanchard, R. E. (2009) The feedback impact on learning, a control systems view. In *Proceedings of the Twentieth Annual Conference of The Australian Association For Engineering Education, Adelaide, Australia 6-9 December*.
6. Abdulwahed, M., & Nagy Z. K. (2009) The impact of the virtual lab on the hands-on lab learning outcomes, a two years empirical study. In *Proceedings of the Twentieth Annual Conference of The Australian Association For Engineering Education, Adelaide, Australia 6-9 December*.
7. Abdulwahed, M., & Nagy Z. K. (2009) Constructivist lecturing with remote experimentation and personal response system. In *the Proceedings of the*

- 9th Annual American Society for Engineering Education (ASEE) Global Colloquium on Engineering Education Budapest, Hungary October 12-15. [CD-ROM].*
8. Abdulwahed, M., & Nagy, Z. K. (2009) Developing a generic architecture of a triple access mode engineering laboratory with LabVIEW, case of the Loughborough Process Control Lab. In *Proceedings of the 9th Annual American Society for Engineering Education (ASEE) Global Colloquium on Engineering Education Budapest, Hungary October 12-15. [CD ROOM].*
 9. Abdulwahed M., Nagy Z. K., & Blanchard, R. E. (2009) Developing engineering learning objects online portal with LabVIEW and open source web content management system. In *the Proceedings of the 9th Annual American Society for Engineering Education (ASEE) Global Colloquium on Engineering Education Budapest, Hungary October 12-15. [CD-ROM].*
 10. Abdulwahed, M., Nagy, Z. K., & Blanchard, R. E. (2008) Beyond the engineering pedagogy: engineering the pedagogy, modelling Kolb's learning cycle. In *Proceedings of the Nineteenth Annual Conference of the Australian Association for Engineering Education (AAEE 2008), to Industry and Beyond, Yeppoon, Australia, M2A3.*
 11. Abdulwahed M., Nagy Z. K., & Blanchard, R. E. (2008) Beyond the classroom walls: remote labs, authentic experimentation with theory lectures. In *the Proceedings of the Nineteenth Annual Conference of the Australian Association for Engineering Education, Yeppoon, Australia 7-10 December.*
 12. Abdulwahed, M., & Nagy Z. K. (2008) TriLab – a combined remote, virtual and hands-on laboratory as a novel reusable learning object (RLO) for supporting engineering laboratory education. *AIChE Annual meeting, November 16-21, Philadelphia, USA.*
 13. Abdulwahed, M., & Nagy, Z. K. (2008) Towards constructivist laboratory education: Case study for process control laboratory. In *Proceeding of Frontiers in Education Conference. FIE 2008. 38th Annual, Springs, New York, USA, 22-25 Oct, pp.S1B-9-S1B-14.*
 14. Abdulwahed, M., Nagy, Z. K., & Blanchard, R. E. (2008) Using feedback control engineering for analyzing and designing an effective lecturing model. In *Proceedings of Frontiers in Education Conference. FIE 2008. 38th Annual, Saratoga Springs, New York, USA, 22-25 Oct, pp.F1C-1-F1C-6.*
 15. Abdulwahed M., Nagy Z. K., & Blanchard, R. E. (2008) Using hybrid feedback control engineering for designing effective project based learning. In *the Proceedings of the International Conference on Engineering Education, ICEE 2008, 27-31. July, Hungary. [CD-ROM].*

16. Abdulwahed, M., Nagy, Z. K., & Blanchard, R. E. (2008) The TriLab, a novel view of laboratory education. In *Proceedings of the international conference on innovation, good practice and research in engineering education, EE2008, Engineering Subject Centre, Loughborough, UK, 14-16 July*.
17. Abdulwahed M., Nagy Z. K., & Blanchard, R. E. (2008) Constructivist project based learning design, a cybernetics approach. In *the Proceedings of the 6th International Conference on Computing, Communications and Control Technologies: CCCT 2008, in the context of The International Multi-Conference on Engineering and Technological Innovation: IMETI 200, June 29th - July 2nd, Orlando, Florida, USA*.