UNDERGRADUATE ENGINEERING LABORATORIES AND THEIR ROLE IN THE DELIVERY OF CDIO CURRICULA

Matt Murphy
University of Liverpool
Liverpool, UK

Brian Surgenor
Queen's University, Kingston
Ontario, Canada

Geoff Cunningham
Queen's University, Belfast
Belfast, Northern Ireland

Abstract

The laboratory was the original hands-on component in undergraduate engineering curricula. The laboratory has fallen out of favour over the years, partly due to resource limitations and partly due the fact that without continuous nurturing by a dedicated faculty member, they tend to devolve to cookbook exercises in data collection. Over the same period of time, the team design project has become a key method for the delivery of a CDIO oriented engineering curriculum. To a certain extent, the design project has taken over the role originally fulfilled by the traditional laboratory. This paper examines the purpose of the undergraduate laboratory, highlights problems associated with lab-based learning, reviews a number of specific examples, and finally lists points for discussion about the role of the laboratory in the CDIO context.

Keywords: design-build, design-implement, laboratories, active learning

Introduction

In the early days of engineering education, instructional laboratories were an essential part of undergraduate programs as they were the only source of the hands-on instruction that was needed to complement the engineering science that was taught in the lecture hall. In a way, laboratories with students working in groups were the first acknowledgement that the best way to teach was to "practice by doing" and "teach others". The "practice by doing" element is also implicitly followed by instructors who believe that the design process is not complete, and the educational impact much less effective, unless the build and test phase of the process is included in design project courses [1]. And although the main reason for requiring students to work in teams in design projects is to provide students with experience in team work, one must also recognize that there is an element of "teach others" in the exercise.

In recent years, the focus of curriculum development has been on the introduction of team based design projects throughout the curriculum, not just in the final year. When a program is subject to an accreditation review, it is these design projects that are put forward as the primary evidence of the "engineering design" units in a program. In parallel to this development, one can observe a decline in the stature of traditional laboratories as a mechanism to deliver instruction in hands-on engineering and in particular the design process. A review of current laboratories reveals that many have fallen into the "cookbook" style that rarely challenges the creative or problem solving capabilities of a student, and they are often performed in large groups, significantly diminishing any educational value that the exercises were intended to have [2].

There is no explicit mention of laboratory exercises in the CDIO syllabus [3], although Section 2.2 of the syllabus covers, in some depth, the topic of ‘Experimentation and Knowledge Discovery’. Many of the topics referenced in the syllabus - Hypothesis Formulation, Survey of Print and Electronic Literature, Experimental Inquiry and Hypothesis Test, and Defense – would be typical of the expectations from traditional laboratories and may perhaps serve as a checklist for laboratory design.

A direct reference to laboratories is made within CDIO Standard 6, which advocates the provision of ‘laboratories that support and encourage hands-on learning of product and system building, disciplinary knowledge, and social learning’ [4]. In the context of this paper the concept of supporting the learning of disciplinary knowledge is possibly most significant.

The Instructional Laboratory

It is useful to distinguish between three basic types of engineering laboratories: development, research and educational [5]. While they have many characteristics in common, there are differences. These differences must be acknowledged if there is to be agreement on the educational objectives for instructional laboratories. It is interesting to note that all three kinds of laboratories can be found in a university setting.

Practicing engineers go to the ***development laboratory*** for two reasons: 1) to obtain experimental data to guide them in the design and development of a product and 2) to determine if a design performs as intended. While a development laboratory is intended to provide immediate answers to questions, a ***research laboratory*** is used to seek broader knowledge that can be generalized, often without a specific use in mind. Finally, when undergraduate students go to an ***instructional laboratory***, they do so to learn something that practicing engineers are assumed to already know. That “something” needs to be well defined through the careful design of learning objectives if the considerable resources devoted to instructional laboratories is to be justified.

In the past two or three decades, several engineering education scholars have spoken to the issue of learning objectives. Beginning with Bloom [6], various taxonomies of learning objectives have been developed that help to explain the concept of objectives. However, the literature is relatively silent on the learning objectives associated in engineering instructional laboratories. The majority of papers on the subject of laboratories tend to take the objectives for granted and simply report on the nature of the apparatus and the success of the students in accomplishing a desired task [5]. Furthermore, given the decline in the practical skill development that used to occur outside of school, there has been a trend to use laboratories solely for the purpose of giving students the “look and feel” of physical systems [7].

Common Problems with Lab-Based Learning

The majority of studies concerned with laboratory-based learning have been carried out in the physical sciences, with very few addressing the engineering disciplines. However a review of recent research evidence reveals several characterstic problems associated with UG laboratory work that are common to all technical disciplines.

Insufficient Understanding of the Theoretical Background

In order to properly carry out the lab exercise, and to learn from it, the student must first understand the relevant theoretical background. Time-tabling constraints mean that a student might undertake a lab class many months before or after the theoretical background has been covered in the lecture course. Even when the lab class coincides with the lecture coverage of the topic, the student must consider how the theory relates to the experimental work undertaken. It may be assumed that many students will have neither mastered the theory, nor considered its practical application, in advance of the laboratory class.

Poor Learning Efficiency

Accepted pedagogic theory states that efficient learning depends on the effective use of our 'working memory space': the part of our brain where we all do our temporary holding of information; thinking and reflecting; understanding and applying; analysing and synthesising; problem solving; being sceptical and inquisitive. Working memory space is of a finite capacity: if students are overloaded with new information in the short period during which they undertake the lab, then they have a reduced capacity to think about what they are doing, why they are doing it, and what they are discovering.

> *"Information overload is the most significant barrier to learning"* [8]

Consideration of the typical student experience of laboratory classes allows the challenges they face, and the associated new information they must assimilate, to be identified.

a) *Understanding the theoretical background*

The students must assimilate a significant amount of new information if they are to achieve the required level of theoretical understanding during the lab session.

b) *Familiarisation with the experimental environment*

On entering the laboratory class students will be introduced to apparatus, instrumentation, test specimens etc. that they will not have previously encountered. Also most UG labs are conducted in facilities that the student will not have visited before. A fraction of the students' mental capacity will be engaged, perhaps unconsciously, in adapting to the experimental environment.

c) *Interpreting written and verbal instructions*

It is likely that many students will not have studied their lab script in advance of the class. One of their first tasks will be to determine the aims and objectives of the exercise, the experimental approach, and the reporting requirements. They will also need to listen to instructions and guidance from the Demonstrator.

d) *Conducting experimental work*

The main foci of a lab class are executing experimental procedure; collecting and processing data; and completing the laboratory report. The majority of the students' mental capacity is devoted to operating the equipment and instrumentation; generating and recording results; and writing the work up.

e) *Teamwork & Communications*

Lab classes are conducted in groups and the students must concentrate on their teamwork, task allocation and communication.

g) *Time available for labs*

The traditional approach to laboratory classes requires students to complete the experimental and submit their technical note within the three-hour session, or shortly afterwards. An investigation into student opinions of laboratory classes yielded comments such as:

"Feel like I don't know what the hell I'm doing and have often felt rushed";

"We don't learn any more by having to rush through lots of exercises, we just get stressed and resent having to do them!";

"The main aim would be to leave as quickly as possible" [9]

A significant fraction of the students' attention is spent worrying about completing the tasks in the time allowed.

It is clear that during a typical laboratory class the student must absorb, process and act upon a great deal of new information under time pressure. As a result students can become overloaded and reduced to following step-by-step instructions to complete the experiment. They have neither the time nor the mental capacity to think clearly about what they are doing, why they are doing it, and what they are discovering.

> *'... in the midst of an apparently active learning situation, it is possible for the student to be passive with his brain in neutral'* [10]

For these reasons many studies conclude that the traditional undergraduate laboratories can be an inefficient approach to extending theoretical learning or developing practical skills.

Emphasis on Experimentation not Investigation

The majority of laboratory classes are recipe driven and demonstrator led: students follow detailed instructions to complete a pre-defined experimental procedure, to collect pre-defined results, and draw pre-defined conclusions. Such labs can deliver learning outcomes associated with experimental, numerical and communication skills and this is probably appropriate for Yr0/Yr1 labs. However Yr2 labs should target the development of investigative as well as experimental skills and the traditional 3-hour, recipe driven approach is therefore inappropriate.

Before discussing problems with lab-based learning further, it is instructive to review a number of specific examples.

Conventional Laboratory Example

MECH 350 *Automatic Control Systems* at Queen’s University, Kingston is a third year core course with an enrolment of approximately 175 to 200 students. The content is typical of that found in most mechanical engineering programs on this subject: modes of control, principles of feedback, Laplace and transfer functions, transient response of first and second order systems, stability criteria, root locus, Bode and frequency response. A set of six “mini-labs” is given as part of the course.

- Lab #1 – Introduction to the apparatus and open loop motor speed control
- Lab #2 – Motor simulation with MATLAB
- Lab #3 – P and PI closed loop motor speed control
- Lab #4 – P and PV closed loop motor position control
- Lab #5 – Bode, root locus and time domain analysis with MATLAB
- Lab #6 – Light assembly control with a programmable logic controller (PLC)

The stated objective of the laboratories is to expose students to the hardware and software aspects of automatic control systems.

Each laboratory is one hour in length and the students work in pairs (as illustrated in **Figure 1**). A written group report must be submitted before the end of the laboratory. Twenty-two students can be handled in each one-hour session. Thus, with eight sessions scheduled per week, the entire class can be complete each laboratory in almost one week.

Aside from their short (one hour) duration, these laboratories are organized conventionally:

- Background material on the theory is covered by lectures given prior to the laboratory
- Students follow a written procedure
- Everyone has the same equipment that is set-up by technicians in turn key fashion
- Students record their results and submit their conclusions in the form of a written report.

The main learning objective of these labs is to reinforce the lecture material. Consequently, there is active coordination between the timing of the lectures and the timing of the laboratories. The mechanical and electrical components of the system being tested are “well-behaved” and directly controllable by the students. Given the number of students and tight timelines, hardware (and software) failures are to be avoided and system reliability is paramount.

Unconventional Laboratory Example

MECH 452 *Mechatronics Engineering* at Queen’s University Kingston is a fourth year elective course with an enrolment of 40 students. The course objective is to extend a student’s working knowledge of engineering to include applied electronics and microcontrollers. The course is designed around a laboratory sequence using a microcontroller based prototyping board and a mobile robot that was designed in-house. The labs alternate between applying the technology to the prototyping board in one week, and then applying the same technology to the mobile robot in the following week:

- Lab #1 and Lab #2, navigation by contact sensing (limit switches)

- Lab #3 and Lab #4, navigation by light sensing (photoresistor mounted on a servomotor)
- Lab #5 and Lab #6, navigation by ranging (infrared sensor, with Lab #6 illustrated in Figure 3 where the robot is required to follow the centerline of a test track)
- Lab #7 and Lab #8, navigation by RF (wireless communication)

The laboratories are conventional in the sense that they are relatively tightly scripted. A handout details the procedure and every group works with the same component hardware. Variation between groups arises from the programming and in the handling of the sensors, actuators and supporting electric circuits.

For these laboratories, students work in pairs, and this occupies the first eight weeks of the course. The underlying goal is to introduce the students to the technology such that they become comfortable with the technology and gain confidence in their own abilities. As seen in **Figure 2**, one aspect of these labs is that even though the students work in pairs, the performance evaluation is done as a group.

In the final four weeks of the course, the experience and knowledge gained in the laboratories is applied to a team design project. In this case, “team” means eight students working together with four robots. To date, the project has involved a problem that mimics a team of autonomous robots trying to find and isolate multiple landmines (represented as lights). This particular task was chosen as it makes use of all of the technology learned in the first part of the course. Also, it models a very real and significant application of multiple autonomous mobile robots (landmine detection and isolation). **Figure 3** illustrates the development phase of the project. The students learn very quickly that one of the biggest problems is that of spurious and faulty sensor readings. Considerable design time is spent addressing this problem, typically by the application of redundant sensors in combination with innovative programming.

Discussion on Specific Examples

Aside from the subject matter, one different aspect of the MECH 452 laboratories versus those in MECH 350 is that even though the students work in pairs at their own workstations for the development phase (similar to **Figure 1**), the “testing” phase is conducted as a group, as illustrated in **Figure 2**. The immediately obvious impact of group observation of the testing demonstrations is the level of effort that performing in front of your peers inspires. Beyond the quest for marks, students clearly take pride in a successful demonstration and associate “coolness” with a particularly creative and elegant solution. Laughter is in the room and everybody claps and applauds each other’s performance.

There is significantly more than a motivational benefit in this process though. Viewing a series of demonstrations that include various design solutions to the same problem, with essentially the same equipment, presents an excellent opportunity for discussing the problem solving process. This is especially effective because everyone shares a very good understanding of the task. Issues such as reliability, redundancy, noise, sensitivity to a changing supply voltage, code size, response time and the smoothness of motion are points of discussion for the instructors, the presenters and the student audience.

Striking examples of previously studied key concepts are bound to occur. For instance, the robot behaviors resulting from open loop or closed loop control are clearly different. The course instructor can expand the thinking about these ideas to include the evaluation of their merit given the task at hand. How much programming and testing effort did the different solutions require, and was it worth it in light of what was required to meet the test criteria ? This is essentially a discussion about design constraints. Frequently, students in MECH 452 spend time discussing their capstone design projects with the instructors and regularly incorporate some of the mechatronics material into their final design work.

In the process of putting a lot of focus on making an effective teaching laboratory experience for the student, one notices a shift in the way that lectures are prepared. While laboratories have long been used to illustrate the points made in the lecture, and they still do, the preparation process has altered. With the key concepts to be illustrated in mind, one looks for the laboratory experience that will bring about that particular learning experience. Then the lectures are built to prepare for the students for the laboratory with the essential concepts, background information, and detailed notes on the equipment that the students will use. Finally, each lecture following a laboratory will include some review of what was learned, with particular references to what actually happened in the laboratory.

Discussion Points for Round Table General Discussion

The examples of laboratories presented here require significant material, instrumentation and teaching staff resources. However, their worth needs to be viewed with the understanding that their value goes beyond simply being interesting supplements to lecture material.

This paper is meant to prompt discussion at a Round Table Session. Discussion points include:

- objectives of a laboratory versus those of a team design project ?
- CDIO context of a laboratory versus that of a team design project ?
- workshops versus laboratories, the difference ?
- prescriptive versus descriptive laboratory procedures ?
- standalone laboratory course or as a component of a lecture course ?
- coordination with lectures, laboratories first or lectures first ?
- evaluation methods and the dreaded written laboratory report ?
- table top models or full size apparatus ?
- one hour mini-laboratories versus three hour traditional laboratories ?
- pre-laboratory exercises as prerequisite for a laboratory admittance ?
- student survey results for opinions on the different formats

Summary

This paper examined the purpose of the undergraduate laboratory, highlighted problems associated with lab-based learning, reviewed a number of specific examples, and finally listed points for discussion about the role of the laboratory in the CDIO context.

References

[1] Singhal, A.C, Bellamy, L. and McNeill, B. "A New Approach to Engineering Education", Arizona State University, Arizona, pp. 88, 1997.

[2] Surgenor, B.W., and Firth, K. "The Role of the Laboratory in Design Engineering Education", *3rd CDEN Int. Design Conf.*, July 24 to 26, Toronto, Canada, 2006.

[3] Crawley, E.F. "Creating The CDIO Syllabus, A Universal Template For Engineering Education", 32nd ASEE/IEEE Frontiers in Education Conference, Boston, MA, 2002.

[4] "The CDIO Standards" Available from: *http://www.cdio.org/tools/cdio_standards.html* [Accessed 21 May 2008]

[5] Feisel, L.D. and Rosa, A.J. "The Role of the Laboratory in Undergraduate Engineering Education", *ASEE Journal of Engineering Education*, January, pp. 121-130, 2005.

[6] Bloom, B.S. "Taxonomy of Educational Objectives", Longmans and Green, New York, NY, 1956.

[7] Leva, A. "A Hands-On Experimental Laboratory for Undergraduate Courses in Automatic Control," *IEEE Trans on Education*, Vol. 64, No. 2, pp. 263-272, 2003

[8] Carnduff, J and Reid, N. "Enhancing Undergraduate Chemistry Laboratories", *Royal Society of Chemistry*, 2003.

[9] Turner, P. 'An Analytical Model for Understanding Undergraduate Learning during Placements and Practical Laboratory Classes', *British Education Research Association Conference*, UK, September 2004.

[10] Johnstone, A.H. and Wham, A.J.B. "A Model for Undergraduate Practical Work", *Education in Chemistry*, Vol. 16, No. 1, pp. 16-17, 1979.

Figure 1. Automatic control laboratory, students work in pairs

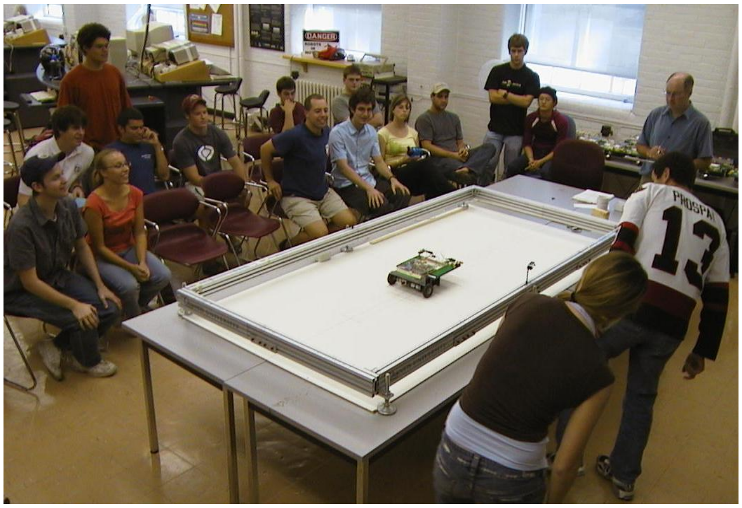

Figure 2. Mechatronics laboratory, students work in pairs, but performance evaluated as a group

Figure 3. Mechatronics team design project, testing in development phase