

# Developing virtual laboratories for introductory control

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**Abstract**—This paper focuses on student access to learning opportunities and in particular those where students can learn by trial and error, such as in laboratories. It is recognised that regular student access to real equipment is a challenge for many institutions and thus alternatives are required, such as remote access laboratories. However, even remote laboratories are non-trivial to make available and thus this paper focuses on virtual laboratories. It demonstrates how these can be formulated very efficiently, can be highly accessible and critically, enhance the student learning experience. Several examples of virtual laboratories are discussed.

**Keywords:** Web accessible laboratories, independent learning, authentic learning

## I. INTRODUCTION

There has been a sizeable body of work in recent years focussed on the laboratory experiences of students within engineering and a reassertion of the long standing view that laboratories form a key component of the student learning experience Abdulwahed (2010). This view is also strongly made by accreditation bodies Council (2011). Nevertheless, it is recognised that laboratories are expensive (Hofstein and Lunueta, 2004) and indeed not necessarily efficient learning activities. Consequently Universities must seek a balance between the benefits of students interacting with equipment and the corresponding expense and inefficiency Lindsay and Good (2005); Ma and Nickerson (2006).

### A. Remote or web accessible laboratories

Many Universities have bought large scale into the concept of remote laboratories, e.g. (RELOAD, 2010; Qiao et al., 2010; LILA, 2010; Nagy and Agachi, 2004; Trevelyan, 2004). These enable departments to overcome many of the constraints associated to putting students into a laboratory room: typically there are restrictions on the number of duplicate equipment sets which means running the same activity numerous times in order to allow the entire cohort to participate and thus puts corresponding pressures on timetables. Consequently, most undergraduate students may only gain access to equipment about once a fortnight, with the exception perhaps of their final year research project.

Remote laboratories overcome barriers such as the timetable as the laboratory is then available 24/7. In principle, these laboratories can also be much cheaper as duplicate sets are not required and moreover, there is a not a requirement to find space for students to access the equipment (many universities now deploy space charges). With the right interface, especially

with a suitable webcam, it is clear to students using a remote laboratory that it is real equipment and the data they are receiving is authentic.

Nevertheless, remote laboratories also have significant failings. Where the activity has a relatively slow timescale, there is still a need to allocate students specific access times. Even when the activity has a fast timescale, students may still need access for 5-10 min to complete their tests and this would be a severe irritation to students in a queue for access. With large class sizes, it is apparent that remote and web accessible need not imply there is good accessibility, which in turn could lead to student frustration.

### B. Virtual Laboratories

One alternative to remote laboratories is a virtual laboratory (Foss et al., 2006; Guzman et al., 2006; Khan and Vlacic, 2006), that is one which emulates real equipment and has the appearance of being authentic, despite being in fact just a simulation. Of course these have limitations (Engum et al., 2003; Magin and Kanapathipillai, 2000) because they are not the real thing, but nevertheless they can be highly authentic if done well (Goodwin, 2010). Moreover, they can form an invaluable component of an overall student activity set Abdulwahed (2010); Callaghan et al. (2008) because they provide activities which emulate much more closely than paper exercises the actual equipment. More specifically, virtual laboratories can form an invaluable preparation for access to real equipment as they can encourage students to think through the key concepts and tests that are required, and thus enable much more efficient use of equipment. Recent work in Southampton is also exploring how good quality video and animation could similarly improve student preparation and this has equally been denoted a virtual experiment (Memoli, 2011).

The main advantage of a virtual laboratory is that the access is much improved over remote laboratories; in principle all students can access simultaneously (unless there are license restrictions on the associated software). This means students have fewer obstacles to engagement and learning through trial and error in an pseudo-authentic scenario.

### C. Summary

This paper focuses on the role and development of virtual laboratories. The role is largely to support student learning and provide an accessible pseudo-authentic experience which helps students relate lecture content to real life scenarios, and

thus improve insight and understanding. However a secondary and equally valid role can be to facilitate preparation for a real experiment. The virtual laboratory can emulate activities and concepts required for the actual laboratory (Abdulwahed, 2010; Memoli, 2011) and thus enable students to prepare effectively.

The second contribution is to discuss the actual laboratories developed and give some evaluation from students on their views about these laboratories. The focus is on activities which support the learning of fundamental control engineering concepts.

## II. SUPPORTING STUDENT LEARNING THROUGH AUTHENTIC ACTIVITIES

The priority for the author's department was to develop activities to support large cross faculty modules in modules related to control. Given the large size of the cohorts, access to equipment is very difficult in practice and thus remote activities were essential to give students access to more authentic scenarios. The topics of most interest within this paper are:

- 1) In year 1 students learn about modelling and system behaviours with most focus on 1st and 2nd order differential equation step responses. Some experimental activities were wanted to reinforce the concepts covered in lectures.
- 2) Also in year 1, students are introduced the concepts of feedback and PI control. There was a desire for activities that allow students to experiment with the PI parameters in both an emulated environment and on real equipment.

The developments follow the TRILAB concept to some extent.

- Students are introduced to the theory in lectures
- Students access a remote laboratory to test same ideas on real equipment and also to understand the differences.
- Students have virtual laboratories to practise in a pseudo-authentic environment.

Chronologically, the first two bullet points were developed first and thus this section will discuss the theoretical background and the remote equipment. The next section will focus on the third bullet point, which in fact will ultimately become the 2nd activity to help students prepare and thus is a key pedagogical element in the overall learning experience.

### A. Creating a remote laboratory

This paragraph is a summary of key points and is discussed in more detail in (J.A.Rossiter et al., 2011). The development of a web accessible laboratory is surprisingly easy and will be summarised in the following steps.

- 1) Connect up the hardware to the computer with a compatible I/O card. The authors found National Instruments cards easy to link into LabVIEW thus saving time.
- 2) Develop and test your LabVIEW virtual instrument (vi) or programmes' for communicating and controlling the experiment. The Front Panel window of the LabVIEW



Figure 1. The DC servo equipment

will be displayed to the user and it can be designed in a user friendly manner.

- 3) Once the experiment is working under a local computer it is a one click operation to use the web publishing tool to generate a web link for the vi and publish this link in your website. Students can then control the equipment via a web interface as if sitting next to the equipment.
- 4) There are some minor requirements on plug-ins for the browser to display correctly, e.g. Vision Development Module Run Time Engine and LabVIEW 2009 Run Time Engine.

### B. Activity 1 and equipment (J.A.Rossiter et al., 2011)

The first activity is focussed on reinforcing student understanding of first order dynamics. In lectures students are taught to derive and analyse first order models and thus to understand the links between model parameters and behaviour as well as analogies between different systems. A laboratory can reinforce this by demonstrating:

- 1) Real systems do indeed have responses that are closely modelled by a first order response.
- 2) The system model parameters can be estimated reliably from measured data.
- 3) Real responses differ slightly from ideal behaviour.

The main parameters in a first order model are gain and time constant. Consequently the laboratory activity is split into three parts: (i) estimate the gain; (ii) estimate the time constant and (iii) compare the estimated model response with the actual behaviour.

The equipment selected is a simple DC Servo motor kit (see figure(1)) with analogue inputs and outputs. It consists of 5 different units in addition to nonlinearities. The students can see the axle rotation and the display showing angular velocity. Within the experiment the only input used is the input voltage as the response from voltage to angular velocity is approximately first order.

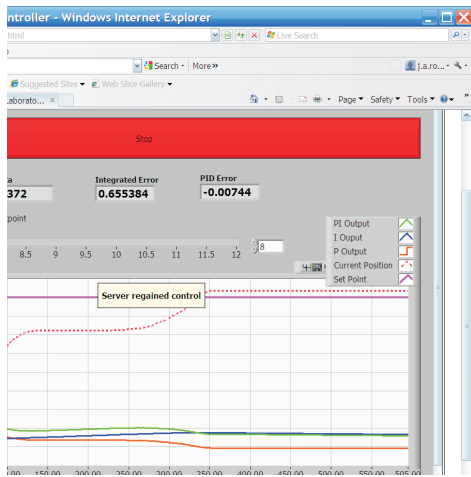


Figure 2. Interface for the stig equipment

The remote laboratory interface has three separate tabs. In tab one students modify the input voltage directly to estimate the steady state gain, positive dead-zone and negative dead-zone of the DC servo motor. Gain is given as the gradient of the input/output curve. In tab two, the time constant of the system is estimated using responses to a square wave input. In tab three, students enter their estimated gain and time constant and produce an exact step response to compare with the plots from tab two.

### C. Activity 2 and equipment

The second activity (internally denoted as 'the stig') is designed to reinforce student understanding of PI control and basic control concepts. The underlying objectives are for students to investigate:

- 1) The impact of changing gain with no integral.
- 2) The effect of changing integral with no proportional.
- 3) The potential of using proportional and integral together.

The equipment consists a cart on 2 metre long rails. The cart is moved by a motor. The underlying dynamics are such that in the future the same equipment will be suitable for experiments looking at 2nd order modelling and dynamics (e.g. under damped responses) as well as an introduction to feedback.

The remote interface is very simple in form. Students are able to choose a proportional term, an integral term and a set point. The system begins moving and the final interface is a button which allows them to stop the experiment at a point of their choosing. The graphical display (figure 2) shows the output position, the input signal, the output of the integral term and the output of the proportional term for the entire runtime.

The interesting point to note here is that there is clearly some stiction in the system so although, with patience, the system will progress close to the desired steady-state, it never quite gets there because the change in input needs to be large enough to get the system moving again and then it tends to jump. However, stiction aside, the expected behaviour does

ensue so the experiment gives students a good insight into reality and the relevance of the theory covered in lectures. Moreover, it allows them to see the role of the integral term (blue line) and proportional term (orange line) in the overall input signal (green line); this is particular important for understanding the real system effects such as stiction because students can see the cart stalls even when the input (and integral term) is changing.

### D. Laboratory design: pedagogy and learning outcomes

Access to the equipment itself is not, in general, enough to support student learning. The authors have experienced significant frustrations due to software and hardware crashes which limit student access until the crash is noted and rectified manually. Although some crashes can lead to an automatic reboot J.A.Rossiter et al. (2011), this is not the case for all.

A second weakness of remote laboratories is that only one student can access these at a time. With small cohorts this may not be an issue, but with cohort sizes of 100 plus, the likelihood is that students will have similar free periods and will all try to access simultaneously. Consequently they may have to wait a substantial period to come first in the queue, and their position in the queue will not be obvious without substantial increase in complexity of coding at the server end. This weakness will limit their ability to learn by a large number of trial and error experiments, something staff may wish to encourage.

Consequently, the next section looks at how students can spend time focussing on learning concepts and thus require less time on the equipment to validate the authenticity of their learning.

## III. VIRTUAL LABORATORIES TO SUPPORT PREPARATION FOR REMOTE LABORATORIES

The key aim of the virtual laboratories is to provide maximum accessibility for students to practise. One could argue therefore that web interfaces such as (Khan and Vlacic, 2006; Guzman et al., 2006) are ideal. However, the downside of such laboratories is the skill and time required to develop them, as well as the need for a maintenance of an appropriate server. Consequently, the authors decided to follow a route which minimised the staff skill and time requirement, as this is pragmatic and increases the potential for more staff to participate.

In summary, it was decided to use MATLAB/SIMULINK as the base for virtual laboratories.

- 1) The relevant files can be distributed easily for students to use anytime and anywhere.
- 2) MATLAB is available on the University network and thus students have excellent access to the software. Many students also purchase a student version for home use or can get remote access to the University software with the relevant 'access code'.
- 3) The software is well understood by most staff and widely used, thus making resources easier to produce and share.

- 4) The author's department also has a well established server system which students can access remotely to run MATLAB files.
- 5) The GUIDE tool allows for relatively straightforward production of GUIs which make interaction easy and intuitive for students.

The virtual laboratories are designed as far as possible to emulate the physical laboratories so students go through the same steps and focus on the same concepts. This will allow them to become familiar with the key observations expected before accessing the equipment and moreover they are more likely to notice the key differences between the theory and the practice.

In terms of staff effort, each GUI took about half a day to create which is much quicker than requirements with alternative software choices.

### A. Virtual Modelling laboratory

This laboratory was focussed on 1st order modelling. To allow some non-linearity and add realism, the simulation is based on a simulink model which has simple first order dynamics but with some dead zones and measurement noise also added. The virtual laboratory was produced as single GUI (figure 3) which embodied all 3 activities of the experimental equivalent and hence it required:

- Three axes, one for each activity.
- Buttons for changing the input voltage and saving data.
- Boxes to enter the estimates for gain and time constant.

The top right axis shows the steady-state vs the input, marked by crosses, for different inputs and also a best estimate of the slope; clearly the slope is an estimate of gain. The input voltage is selected by a slider, a button requests a simulation with this value and another button confirms the data should be entered into the plot (so a student need not save all values). The little circle in the top middle emulates the spinning of the servo and rotates in real time on the GUI, as well as showing the steady-state speed. The reader will note some stiction is included in the simulation so there is no movement for small voltage inputs. For completeness, figure 4 shows the equivalent interface on the actual equipment. This has separate axis for positive and negative input voltages but otherwise is seen to have equivalent functionality: the webcam is used for students to read the speed, there is box to enter this reading and another button to *add data* to the axes - this data is also displayed in numeric form. Students are also encouraged to identify the dead zone and enter the observation into the relevant boxes.

The axis in the bottom left shows the responses to a square wave, with the same input amplitude as for the first figure. Some noise is added to encourage students to think about real issues. This display can be used to estimate the time constant.

The axis in the bottom right is used to simulate a model based on the gain and time constant estimates. Students must enter their estimates into the boxes provided.

The main objective of the GUI was to allow students to go through the same conceptual steps required for the

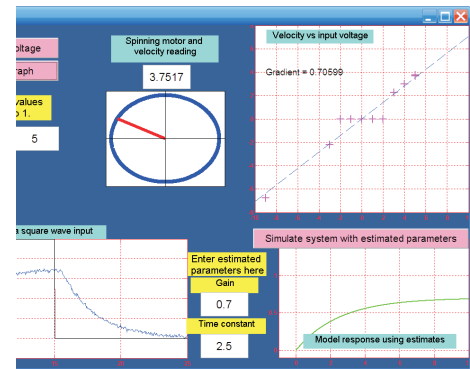


Figure 3. MATLAB GUI for 1st order modelling.

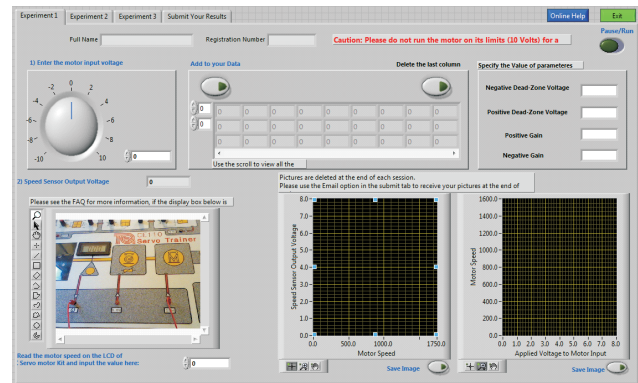


Figure 4. Interface for activity 1 on remote laboratory.

remote laboratory. That is practise changing the input voltage, reading the steady-state output and then adding this data to the axis (hence the need to a deliberate button press). The remote laboratory will produce a similar figure containing the crosses, although in that case students need to estimate the slope themselves and then enter into a box. The bottom axis gives a very similar plot to that students would see on the real equipment, with a square wave response. From this, in both cases, the activity required is an estimate of time constant. Finally, the third activity in both cases is to use the gain and phase estimates to from an ideal 1st order model and simulate the step response. The intention is that students would therefore find engagement with the remote laboratory straightforward as well as being clear on the key learning outcomes, understanding first order responses.

### B. Virtual PI laboratory

This laboratory is based on position control of a cart (carrying a passenger) along a track. The requirement was for students to explore the impact of changing the PI parameters on performance. Hence the chosen GUI was chosen to be very simple in form as shown in Figure 5. There are simple sliders for entering the choice of proportional and integral terms. The top axis shows the target and output position curves (in figure 5 there is a steady-state offset as the integral is zero). The bottom axis is an animation and students see the passenger

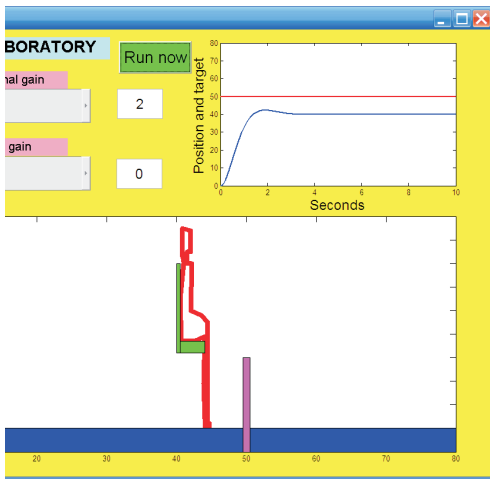


Figure 5. MATLAB GUI for PI control of position.

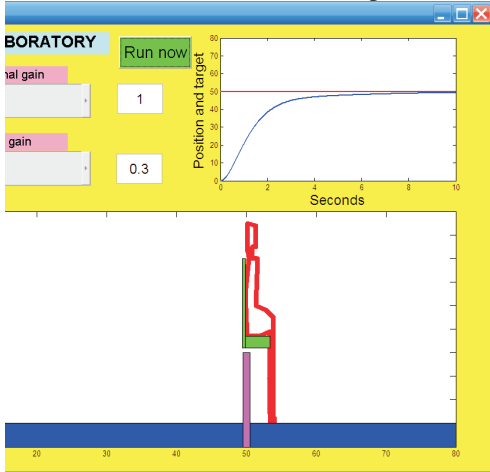


Figure 6. MATLAB GUI for PI control of position.

moving but ultimately stopping short of the target. Figure 6 shows a simulation with a non-zero integral where clearly the offset is removed.

For completeness, figure 2 shows the associated hardware laboratory interface, accessible via the web. Again, students need only set the PI parameters and while the same basic observations will follow, it is clear that the behaviour is far from ideal; this should give students something challenging to ponder.

#### IV. STUDENT EVALUATION

It is known that remote laboratories can be beneficial and hence the main focus of the evaluation here is on the efficacy of the virtual laboratories for enhancing the overall student learning experience. Students were asked a number of questions and the responses are summarised in Tables 1 and 2. Table 1 is a smaller student group who had the virtual laboratories paired with a hardware laboratory. Table 2 is a much larger group (over 200) who had the virtual laboratories solely for supporting learning, but not for assessment.

It is interesting to note that the second group were less positive overall, but this is probably a reflection of their

TABLE I  
STUDENT EVALUATION OF VIRTUAL LABORATORIES (ACS108).

Question	Strongly agree or agree	Neither agree or disagree	Disagree
Virtual Laboratories (MATLAB GUIs) were easy to use and access	89%	7%	4%
Virtual Laboratories helped me prepare for the remote laboratories	75%	21%	4%
I felt more confident using the remote laboratories having first gone through the virtual laboratories	50%	38%	12%
It was useful to see the differences between a simulation (ideal model of virtual lab) and the responses on real equipment.	89%	7%	4%
The modelling virtual laboratory helped me understand the key parameters of gain and time constant	75%	18%	7%
The STIG virtual laboratory helped me understand the role and impact of the key parameters of P and I	82%	14%	4%
I think the department should produce more virtual laboratories to support preparation activities for laboratories.	92%	4%	4%
I think the department should produce more virtual laboratories to support learning of key concepts.	96%	4%	0%

engagement being formative rather than summative and hence many of this group will not have used the virtual laboratories effectively, if at all (many students only put in effort if 'it counts'). Indeed a question on an issue not related to this paper showed that only about 50% of the class had engaged with a key formative resource.

Where engagement was summative, that is for the ACS108 students, it is clear that the resources were useful for the majority. The relatively poor response on preparation for the actual remote laboratories is more likely a reflection of the poor reliability of the remote laboratories so that accessibility was poor and thus many students failed to do the hardware laboratory; this latter issue is an ongoing priority for technical staff.

#### V. CONCLUSIONS

This paper has looked at the provision of laboratory activities within engineering curricula and proposed that the role of the virtual (and remote) laboratory has much more potential than is being exploited in most institutions. Virtual laboratories have the advantage of being accessible 24/7 and also allow parallel access by a large number of students, sometimes the whole cohort.

This paper has illustrated two simple uses of virtual laboratories. The most basic use is as a formative learning exercise, to allow students to practise with key concepts and thus to improve their understanding. A second and more integrated use links the virtual laboratories with real equipment and

TABLE II  
STUDENT EVALUATION OF VIRTUAL LABORATORIES (ACS124).

Question	Strongly agree or agree	Neither agree or disagree	Disagree
The virtual laboratories helped me understand the role of modelling and simulation in design.	84%	7%	9%
Virtual Laboratories helped me prepare for the remote laboratories.	75%	21%	4%
The virtual laboratories helped me understand the role and impact of the feedback parameters P and I.	49%	35%	16%
I think the department should produce more virtual laboratories to support the learning of key concepts.	72%	23%	5%

summative assessment. Virtual laboratories can be used to emulate the activities, concepts and questions students will face in an actual laboratory and thus provide a tool for preparation so they get more out of valuable time on the equipment. The combination of real and virtual laboratories also draws students' attention to the differences between theory and practice. Student evaluation has reinforced the efficacy of the approach.

The final contribution of the paper is to discuss practical issues of developing virtual laboratories. This paper has proposed the use of MATLAB/SIMULINK GUIs. The creation of GUIs with very similar interfaces and inputs to the actual hardware is a relatively straightforward coding exercise using the GUIDE tool, especially as most systems and control engineering staff have some proficiency with MATLAB. This has the advantage that virtual laboratories can be created relatively quickly. A second advantage of this proposal is that many Universities provide site licenses and thus student access is straightforward.

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