Using interactive tools to create an enthusiasm for control in aerospace and chemical engineers

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Abstract: The efficacy of virtual laboratories in supporting student learning is now well accepted. This paper builds on that assumption and considers where there are obvious gaps in provision and a need for a response to typical student criticisms. Specifically here, the focus is on students who complete a control course and do not understand why they have studied it, why it is relevant and so forth. Four new interactive laboratories are introduced which are designed for aerospace engineers and chemical engineers. The former two focus on a context, to help aerospace students see a scenario where lead and lag design might be needed. The latter two, for chemical engineers, focus on uncertainty and why control is therefore essential to ensure good process outcomes.

Keywords: Virtual laboratories, staff efficiency, student engagement, independent learning.

1. INTRODUCTION

The growing potential and recognition of the role of interactive laboratories is well recognised and indeed the special session in the IFAC world congress to which the paper is submitted is evidence enough. Most engineering academics understand that laboratory activities provide a dual role of motivation, that is allowing students to see the application of their learning to real scenarios, alongside a reinforcement of the learning and an appreciation that real applications are not exactly the same as theory. Of course, a typical challenge is that both the timetable and infrastructure may limit student access to hardware. In the UK, some Universities are responding to this with huge buildings projects (DIAMOND (2016); STEMLAB (2016)) dedicated to improving laboratory access and quality. Nevertheless, often creative alternatives are required to ensure students receive adequate exposure to such activities (e.g. Abdulwahed (2010); Qiao et al. (2012); Rossiter et al. (2011) as, irrespective of infrastructure, timetabling and health and safety are fundamental obstacles to student access.

1.1 Background on remote and virtual laboratories

A popular alternative in recent years is the so called virtual laboratory. The focus on virtual laboratories as opposed to say remote laboratories (RL) (Dormido et al, 2012) is for a few simple reasons:

- RL can be expensive to design and build and moreover may require significant ongoing staff support and expertise to maintain, especially during periods where students are expected to be active users (Chen et al., 2013; Vargas et al., 2011; Rossiter et al., 2011). Most departments do not have the expertise or resource to support this activity effectively.
- RL may still suffer from poor accessibility as only a single student can access at a time and thus may be ineffective with large groups and/or experiments with slow dynamics.

On the other hand, virtual laboratories (VL) need not suffer from access restrictions (unless there are software license issues) and nor suffer from the tedium of slow dynamics as they can be run *faster than real time*. This means that even with very large classes (the author has class sizes of around 400) and building access limited to normal working hours, students can still access a VL whenever it suits them and indeed, from the comfort of the bedroom if they want. It is unsurprising therefore that VL are becoming increasingly common (Cameron, 2009; Goodwin et al., 2011; de la Torre et al., 2013; Fabregas et al., 2011; Perez et al., 2011; Guzman et al., 2006; Rossiter, 2012, 2016).

1.2 Paper assumptions

This paper takes for granted that the role of VL in University engineering education is accepted and focuses on areas where some laboratories can usefully be developed. A second assumption taken in this paper (Rossiter, 2016) is that it is reasonable to build such activities using MATLAB as:

(1) It is increasingly common for all students to have access to MATLAB (in the author's institution all students get a free student license during their studies).
(2) It has the advantage of saving development time and minimising programming expertise requirements for

staff and often these two are the main obstacles to developments.

In summary, although the animation and drawing quality in MATLAB is somewhat crude as is seen in the figures [1], it is clear enough to represent a real engineering system and thus communicate to the student the real context. It is easy to add in interactivity so that the student can *play* and thus learn by trial and error, as well as be systematic. In the author's experience, a reasonable interactive virtual laboratory can be coded in between 4-8 hours depending on the specific requirements, and thus time and expertise are much smaller obstacles.

1.3 Contribution summary

In summary, this paper proposes a pragmatic approach to virtual laboratory development and here the focus is on four new VLs which have designed to tackle specific needs in the curriculum.

(1) Aerospace students on a general control course (joint taught with other engineering disciplines) often comment that they cannot see the link to aerospace of Bode diagrams, lead/lag designs and so forth. Obviously one can introduce some case studies in lectures, but in truth, with a broad based engineering cohort, very limited lecture time and a large number of topics, the space for aerospace specific case studies is very limited and is often left to student background reading (which many students do not do).
(2) A common criticism on classical control courses is an inadequate treatment of uncertainty which is the main motivation for feedback in the first place. Yet, a typical first course will have little if any direct treatment of uncertainty and thus students often fail to grasp this critical factor.

Consequently this paper introduces four new MATLAB interactive GUIs designed to meet the above challenges. These GUIs are freely available to the international community (Rossiter, 2015) along with brief Youtube introductions to the underlying modelling and operation.

Section 2 will give a brief review of the MATLAB GUI environment. Section 3 introduces the GUIs designed for aerospace students and section 4 introduces the GUIs developed, in a chemical engineering context, to help focus on uncertainty. The paper finishes with conclusions.

2. BACKGROUND ON USING MATLAB TO DEVELOP VIRTUAL LABORATORIES

A summary of how to use the MATLAB guide interface to produce interactive GUIs/VL has been discussed briefly elsewhere (e.g. Rossiter (2016, 2012)) and hence this section is deliberately concise and included mainly for completeness.

The guide interface allows the user to develop an interface in an intuitive fashion.

- A palette of commonly used interactive buttons can be dragged into the window and sized and positioned using the mouse. These include sliders, pushbuttons, editable text, axes, radio buttons and more.
- Once the window design is complete, the user saves and MATLAB automatically builds a partner m-file with separate sub-functions for each interactive item. When the user selects the relevant item, any code in the relevant sub-function is activated. Thus it is easy and intuitive for the designer to implement, via code in the sub-functions, animation effects based on student interaction with the interface.
- Basic competence with MATLAB programming is sufficient to develop moderately elaborate interfaces as the guide environment looks after all the challenging interface aspects in the background.

A key aspect, in the author's view, is that the interfaces should include significant animation and pictures to represent real systems. The rationale is that the VL is being used in lieu of access to equipment and thus must represent the movement in that system as authentically as possible in order for students to make clear mental images of the relevance. While the pictures representing the systems may be relatively crude (cartoon like), they should nevertheless be good enough to convey a clear mental image.

3. AEROSPACE EXAMPLES

This section will illustrate two examples of virtual laboratories aimed at helping students see the relevance of lead and lag compensator design to aerospace and moreover, to reinforce some core design principles. Each example is described in separate subsections.

3.1 Dynamics and GUI for antenna tracking problem

The context behind this scenario is an antenna tracking a flying object, for example an aircraft or possibly even a satellite. One interesting aspect to this problem is that such a tracking problem is almost equivalent to tracking a ramp and thus the context can be used for the following two learning outcomes:

(1) Learning and implementing steady-state offset computations.
(2) Understanding the role of lag compensators in reducing offset to ramps.

For simplicity the dynamics of the antenna are taken as similar to a DC servo and thus take the form:

$$\theta(s) = \frac{C}{s(s+a)}u(s) \tag{1}$$

where θ is the angle at which the antenna is pointing and parameters C, a be changed by the user and thus allow different design challenges. A moving object, over short periods, can be assuming to have a trajectory given as:

$$\theta_d = kt \tag{2}$$

where k is proportional to speed/distance and t is time.

A lag compensator is given as:

$$K(s) = K_{lag}\frac{s+w}{s+w/r} \tag{3}$$

For this GUI, K_{lag} is chosen to give a 60 degree phase margin when $r = 1$ and thus students do not choose this value. This is so they can focus on the impact of the

[1] Such simplicity can help raise a laugh in lectures which ironically may improve student learning as it becomes memorable.

parameter r which is the gain uplift at low frequency. In consequence, the gain cross over frequency w_c is 'known' and w is chosen as $w = w_c/10$ as this is a typical good practice guideline.

Control objective: An antenna can see any object within $\delta\theta$ radians of its line of view and therefore can track a flying object as long as the error in angle is less than $\delta\theta$. Consequently, a student task would be to compute the steady-state offset to a ramp and, if necessary, reduce this by the suitable implementation of a lag compensator, or more specifically, a suitable choice of r.

The remainder of this section describes the GUI created by the author for this scenario. A short video demonstrating how to run and use this file is available on this link [http://controleducation.group.shef.ac.uk/matlabguis.html].

A screen dump of the VL is shown in figure 1. The student is able to change the parameters of the antenna model, namely C, a and also the low frequency gain uplift of the compensator r and the ramp rate (rad/s) of the target. The GUI includes an animated picture of the antenna chasing the flying object (denoted as a star) and clearly shows that angle of pointing never quite matches the target, but may be close. As the target speeds up, the offset gets bigger, but this can be reduced by increasing r. The radar and target spin in the GUI giving some dynamics for the user to appreciate the context.

Fig. 1. Screen dump of antenna tracking GUI with lag compensation.

3.2 Dynamics and GUI for control of aircraft roll with a lead compensator

Some aircraft dynamics are challenging and bordering on unstable. Students may be exposed in lectures to the notion that often challenging dynamics may require lead compensation in order to achieve reasonable phase margins and indeed, to get stability in the first place. Roll control is a nice example to demonstrate this principle as, with some simplifying assumptions, one can represent the roll angle ϕ of an aircraft by the following model.

$$\phi(s) = \frac{C}{s^2(s+a)}u(s) \tag{4}$$

where u is the aileron deflection.

It is clear that such a system, due to the presence of two integrators, cannot be stabilised by simple proportional feedback alone. However, a lead compensator of the form:

$$K(s) = K_{lead}\frac{s + w/\sqrt{r}}{s + w\sqrt{r}} \tag{5}$$

offers positive phase rotation and thus, with judicious selection of the parameters, can give closed-loop stability and reasonable performance.

Student activities: In this GUI (see figure 2) more is demanded of the student. They are able to choose the model parameters C, a and also all three compensator parameters K_{lead}, w, r. The intention is that, offline, students engage with a formal lead design technique and then implement these values on the GUI to see how effective their design is. The GUI offers a number of interactive elements to support student learning and engagement.

(1) An animated cartoon picture of an aeroplane undergoing a roll manoeuvre. From this students can clearly see dynamics such as overshoot and oscillation and how these vary with different compensator designs. The plane will even flip due to instability.
(2) A bode diagram and a root-loci diagram which show the original system and the compensated system. The bode diagram information in particular underpins the likely lead design and allows the student to view the margins and cross over frequency resulting from their proposed design.
(3) The animation runs for a fixed time scale in order to capture a demanded change in roll angle.

This GUI is available for download at the following website: [http://controleducation.group.shef.ac.uk/matlabguis.html]

Fig. 2. Screen dump of the GUI interface of the aeroplane roll angle activity.

4. GUIS DEMONSTRATING THE ROLE OF FEEDBACK IN COUNTERACTING UNCERTAINTY

Two GUIs are described in this section; both are taken from scenarios of most direct relevance to chemical engineers although they are of course good examples for most engineering disciplines. The key focus in both cases is seeing the impact of uncertainty and, by student trial and error through the interface, recognising that both open-loop and manual control and likely to be ineffective in general. The GUIs both include a well designed auto-tuned PI compensator to provide a comparison.

4.1 Heat exchanger GUI with uncertainty

A heat exchanger is a very common system in chemical engineering and indeed in most engineering. The dynamics are relatively simple and can be approximated by a first order model with two inputs: (i) the heat supply and (ii) disturbances such as the ambient temperature and temperature of the inlet flow (e.g. δT_{in}). However, in addition to temperature disturbances, one can also have unexpected changes (δF) in the flow rate through the heat exchanger and this has a significant effect on the dynamics as is seen from the model equation below. The GUI allows students to switch the disturbances on and off, but when **on** the impact on the output temperature (performance) is emphasised by changing the values of $\delta F, \delta T_{in}$ every 60 seconds.

A simple model can be summarised as follows:

$$VC_p\frac{dT}{dt} = \lambda Q + FT_{in} - FT \tag{6}$$

where V is the volume, T is the outlet temperature, T_{in} is the inlet temperature, C_p the specific heat of water, λ the latent heat of steam/water and F the flow rate through the heat exchanger and Q is the flow rate of steam (condensing steam provides the heat supply). For clarity it is worth re-writing this equation with the disturbances $(\delta F, \delta T_{in})$ clearly enumerated.

$$VC_p \frac{dT}{dt} = \lambda Q + (F + \delta F)(T_{in} + \delta T_{in}) - (F + \delta F)T \quad (7)$$

It is clear that both the time constant and gain, and thus nominal behaviour, are affected by these disturbances.

The interface is shown in figure 3. From this it is clear that students are able to select a number of parameters such as the nominal V, F, Q, T_{in} and the control mode. Text boxes and the red/green line plots are used to illustrate how the actual values of F, T_{in} vary from the expected values; these are scaled in the line plot to make the changes clearly visible on the same scale as the temperature.

Student activities: Students are encouraged to try and achieve an outlet temperature of 30^0 using open-loop and manual control. Unsurprisingly given that the disturbances change relatively frequently, open-loop control is hopeless; this is clear from figure 3. Perhaps, more surprising to the students is that manual control is very difficult (they can move the Q slider real time to change the steam flow and thus attempt to control the outlet temperature much as you would control temperature in a shower). Readers who wish to attempt this will find it challenging and more significantly, even for students who manage to achieve satisfactory manual control, they will quickly recognise that doing this 24/7 is impossible. Having establishing the weaknesses of humans being responsible for the temperature control, students can attempt automatic control. To reduce the number of interactive buttons on the GUI (simple is often better and less confusing for users), an auto-tuned PI is available where the parameters are based on the nominal V, F. It is very quickly apparent (see figure 4) that this is superior to manual control, even over short periods.

Fig. 3. MATLAB GUI for heat exchanger in open-loop/manual mode.

Fig. 4. MATLAB GUI for heat exchanger under PI control.

4.2 GUI for control of level in a tank with disturbances

The final GUI discussed in this paper is linked to level control in a tank. The dynamics of such a process can be very simple when one assumes the outlet flow is in proportion to the depth (a linearised approximation). In summary, a simplified model is:

$$A \frac{dh}{dt} = F_{in} - Rh \quad (8)$$

where A is the cross-sectional area, F_{in} is the flow in, R is in effect a resistance to outlet flow and h is the depth.

Uncertainty is added into this system by allowing:

- Random changes in the parameter R. This is to represent temporary blockages, stiction in taps, back pressure and so forth.
- Random changes in F_{in} compared to that expected. This is to represent inaccurate control of the in flow as well as unexpected spillages and the like from upstream effects.

In consequence, the actual system model becomes:

$$A \frac{dh}{dt} = F_{in} + \delta F_{in} - (R + \delta R)h \quad (9)$$

The GUI (see figure 5) randomly alters δT_{in} every 300 seconds, but within reasonable limits. Students are able to alter the nominal F_{in}, A using sliders and also to choose both R and $R + \delta R$ directly, that is to specifically state the modelling error in the outlet pipe resistance, and to change this at will.

Student activity: Some of these activities are analogous to the heat exchanger. Students can attempt to use open-loop control and manual control to achieve the desired level in the tank. It will be quickly apparent that changing the fluid in flow rate using the slider is ineffective as a mechanism and even though one can do this to some extent, the ability of humans to deal with the unpredictable disturbances is both slow and poor (and we get fatigued quickly). Having established this, students have two main options: (i) do a systematic PI design and implement these values and (ii) use an auto-tuned PI provided for them. naturally, an instructor can vary the engagement for each student by specifying different A, R and asking students to justify their choices of PI.

Fig. 5. MATLAB GUI to illustrate impact of uncertainty on level control of a tank.

5. STUDENT ENGAGEMENT

In order for such GUIs to have a positive impact on student learning, it is essential that students make use of them. From the author's perspective these can be used for demonstrations in lectures in lieu of real equipment which in general is not feasibly brought into a lecture environment. The relatively fast time scales (much faster than real-time) and the ability to demonstrate, quickly, many different scenarios including disaster, can lighten the mood in a lecture and wake students up.

Nevertheless, a lecture intermission is invariably brief and easily forgotten and a well known teaching mantra is that students must do something themselves in order to really understand and remember. Consequently, mechanisms are needed to ensure the students have to actively engage with the GUIs in more than a trivial way. The author's mechanism for ensuring this is to embed the GUI usage into online quizzes. In order to answer questions on the quiz, students need to make meaningful and systematic choices on the GUI based on application of learning and understanding relevant to the given module. The inclusion of numerous parameter choices on the GUI enables the author to write questions with 'randomly generated numbers' so that students all get slightly different questions and this reduces the potential for collusion.

Remark 1. Within the author's University students can access or copy the GUI files from a shared folder. Indeed, within the university network they can run the files directly from the shared folder and do not need a personal copy; this process is demonstrated in lectures and reduces to selecting an appropriate folder. External users can copy the files from an open access website (Rossiter 2015) under the MATLAB section. There are additional VLs on the site which readers may also like to view.

6. CONCLUSION

This paper has built on earlier work which demonstrated the efficacy of MATLAB GUIs for supporting student engagement and learning, in lieu of access to hardware laboratories which is often limited. The particular contribution here is to produce virtual laboratories to support specific learning outcomes where it is known that students often struggle.

(1) Lead and lag compensation have been set in the context of aerospace to help aerospace engineers achieve a better understanding of why classical control has important applications in their area, and as by product, to help them understand core design concepts.
(2) Uncertainty is a key motivation for feedback control, but students often fail to grasp this fundamental point as they get side tracked on the mathematics required. Hence, two of the GUIs are designed specifically to focus on the impact of uncertainty and through the animation facility, bring this to life.

Readers are reminded that using MATLAB has some good advantages for many students in that for a large number of Universities all engineering students have easy access to the software (often a personal copy) and thus can use these VL whenever they like and indeed, even without internet access! A second benefit is for staff. The coding requirements are relatively small and thus staff can produce such VL in a relatively short time; the authors viewpoint is better some activity now, albeit slightly crude and limited in functionality, than a perfect resource that one can never quite finish or afford.

As a closing remark, it is worth emphasising one point. Although these GUIs are relatively limited and what one might call *one trick ponies*, this is intentional. In the author's view, a GUI interface with too many different modes and alternatives confuses students and thus may be less effective. Often a simple GUI focussed on a single message is more likely to be an effective teaching tool as students can use it in an intuitive fashion and without confusion or detailed training.

REFERENCES

Abdulwahed, M, 2010, Towards enhancing laboratory education by the development and evaluation of the trilab concept, PhD Thesis, University of Loughborough

Cameron, I., 2009, Pedagogy and immersive environments in the curriculum, Blended Learning conference, 290-294.

Chen, X., G. Song, and Y. Zhang, 2010, Virtual and remote laboratory development: A review. In Earth and Space, Engineering, Science, Construction, and Operations in Challenging Environments, 3843-3852. doi: 10.1061/41096(366)368.

de la Torre, L., R. Heradio, C. A. Jara, J. Sanchez, S. Dormido, F. Torres, and F. Candelas, 2013, Providing Collaborative Support to Virtual and Remote Laboratories. IEEE Transactions on Learning Technologies.

The DIAMOND building, http://www.sheffield.ac.uk/diamond

The STEMLAB building, http://www.lboro.ac.uk/departments/meme/undergraduate/student-facilities/stemlab/

Dormido, S., H. Vargas, J. Sanchez, 2012, AutomatL@bs Consortium: A Spanish Network of Web-Based Labs for Control Engineering Education, Internet Accessible Remote Laboratories: Scalable E-Learning Tools for Engineering and Science Discipline, 11, 206-225, A. Azad, M. E. Auer, V. J. Harward (Ed), IGI Global.

Fabregas, E., G. Farias, S. Dormido-Canto, S. Dormido, and F. Esquembre, 2011, Developing a remote laboratory for engineering education. Computers & Education 57:1686-1697.

Goodwin, G. , 2010, Virtual laboratories for control systems design. http://www.virtual-laboratories.com/(last checked 1/9/10).

Goodwin G.C., A. M. Medioli, W. Sher, L. B. Vlacic, and J. S. Welsh, 2011, Emulation-based virtual laboratories: A low-cost alternative to physical experiments in control engineering education, IEEE Transactions on Education, 54:48-55.

Guzman, J., K. Astrom, S. Dormido, T. Hagglund and Y. Piguet, 2006, Interactive learning modules for pid Control, IFAC symposium on Advances in Control Education.

Perez, J., S. Dormido and L. Vlacic, 2011, Enhancing student learning: On-line interactive laboratory for modelling of real world control system applications, IFAC world congress, pp.7268-7273.

Y. Qiao, G. Liu, G. Zheng and C. Luo, 2012, Design and realization of networked control experiments in a web-based laboratory, Proc. UKACC.

Rossiter, J.A., Y. Baradaranshokouhi, I. Lilley and C. Bacon, 2011, Developing web accessible laboratories for introductory systems and control using student projects, IFAC world congress.

Rossiter, J.A., 2015, Lectures and resources in modelling and control, http://controleducation.group.shef.ac.uk/indexwebbook.html

Rossiter, J.A., 2012, Using MATLAB to create cheap and accessible virtual laboratories, ISEE, 2012.

Rossiter, J.A., 2016, Low production cost virtual modelling and control laboratories for chemical engineering students, ACE 2016.

Vargas, H., J. Sanchez, C. A. Jara, F. A. Candelas, F. Torres, S. Dormido, 2011, A Network of Automatic Control Web-based Laboratories, IEEE Transactions on Learning Technologies, 4, 3, 197-208.