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Developing a student–focused undergraduate laboratory*

Keywords: Control engineering, laboratory development, PID control, A/D and D/A conversion.

W. P. Heath¹, O. Onel², P. M. Green³, B. Lennox⁴, Zhenyu Gai⁵, Zhiwei He⁶ and M. C. Rodriguez Liñan⁷

¹Control Systems Centre, School of Electrical and Electronic Engineering,
University of Manchester, Sackville St Building, M13 9PL, UK
(email: william.heath@manchester.ac.uk).

²University of Manchester
(email: oliver.onel@manchester.ac.uk).

³University of Manchester
(email: peter.green@postgrad.manchester.ac.uk).

⁴University of Manchester
(email: barry.lennox@manchester.ac.uk).

⁵Department of Electrical and Electronic Engineering, Hong Kong
University, Pokfulam Road, Hong Kong (email: gaizyu_china@yahoo.cn).

⁶University of Manchester
(email: zhiwei.he@student.manchester.ac.uk).

⁷University of Manchester
(email: mariadelcarmen.rodriguezlinan@postgrad.manchester.ac.uk).

Abstract

Laboratories are an essential component of our undergraduate curricula in the School of Electrical and Electronic Engineering at the University of Manchester. In this paper we discuss the development of laboratories for one of our undergraduate control modules. Students have been involved at all stages of

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*The material in this paper has been submitted to the 10th IFAC Symposium on Advances in Control Education, Sheffield 2013 [3]

the development and have directed the work. The result is a highly successful laboratory package that has been received with enthusiasm.

1 Introduction

1.1 Background

The University of Manchester, formed by the merger of the Victoria University of Manchester and UMIST, has a long and proud tradition of teaching control to both undergraduate and masters students [1, 11]. Currently the School of Electrical and Electronic Engineering offers undergraduate degrees in Electronics Engineering, Electrical and Electronic Engineering and Mechatronics Engineering. Both BEng (three year) and MEng (four year) qualifications are available. Students are first formally exposed to a systems approach and feedback control in their second year with two modules: Signals and Systems in the first semester and Control Systems I in the second. These are compulsory for all students. Control Systems I is an introduction to classical control with a focus on PID control. Both time domain and frequency domain analysis techniques are covered. Frequency domain design methods are also considered leading to lead-lag compensation. Only continuous time control is considered: discrete time control and state space analysis are introduced in the third year.

Laboratories are integral to the delivery of Control Systems I. Ideally they should both motivate the analytical development and reinforce the key concepts. In 2008 we took the decision to develop completely new laboratories for the module to reflect the natural evolution of the taught module material. Our requirements included the following: the system should be highly visual so that the concept and benefits of feedback control can be easily graspable; the rig should be relatively easy to control allowing flexibility in the laboratory content; both the benefits of PID control and the dangers of high gain control should be readily demonstrable; the rigs should be portable so that a dedicated laboratory is unnecessary; we should have many copies of each rig (and hence the rigs themselves should be relatively cheap). We quickly identified two additional desirable characteristics: the laboratory should exploit hardware and software as well as technical expertise made available via our strategic partnership with National Instruments; the development of the laboratory should be student driven so that it can reflect their interests and needs.

1.2 Development

The specific rig chosen for Control Systems I was the position control of a printer head, inspired by [2] and [5]; this is discussed in 2. It was one of a suite of experiments developed as part of a fourth year team project in the academic year 2008-2009 [7, 6]; this is discussed in Section 3.1. We were fortunate that two members of the team stayed on at Manchester to study for PhDs and were available to roll out the final laboratory. It was first used as part of the undergraduate module in the academic year 2010-2011. The hardware was then modified by a student working as a summer intern; this version was used in the academic years 2011-2012 and 2012-2013. Further modifications were proposed by a second summer intern and our intention is to roll them out for the academic year 2013-2014. The role of summer interns and their recommendations for hardware modifications are discussed in Section 3.2. We have also found the rig useful as a demonstrator for research. This work led to innovative software modifications that were introduced for the academic year 2012-2013. These developments are discussed in Section 3.3.

2 The laboratory

2.1 Hardware and software

The aim of the laboratory exercise is to position the printer head of a standard ink jet printer. In the development the printer was an HP D2560; currently we use an HP Deskjet 3000. The print head drive motor and the positional sensor are disconnected from the printers internal control circuitry (Fig 1). In the initial development the encoder strip was replaced with a resistive wire and the optical encoder was replaced with a small wiper that is held in contact with the wire, forming a potentiometer. In its current format we obtain a digital reading of the printer head position via the position encoder. The controller itself is run on a PC using LabVIEW. Data is communicated to and from the PC using a National Instruments ELVIS II board (<http://www.ni.com/nielvis/>) and a dedicated daughterboard (Fig 2) whose prototype was designed and built during the initial fourth year project. A LabVIEW virtual instrument on the PC is shown in Fig 3.

Figure 1: The important components of the inkjet printer system: taken from [7].

Figure 2: National Instruments ELVIS II and daughter board.

Figure 3: Screenshot of a LabVIEW virtual instrument. This is taken from the undergraduate laboratory for the academic year 2011-2012. The sine wave response show the effects of the nonlinearity.

2.2 Laboratory exercise

If we assume linear dynamics, a good linear approximation of the transfer function response from motor voltage to printer head position is

$$G(s) = \frac{b}{s(s + a)}.$$

The break frequency can be modelled as occurring at about 17Hz although in experiments it is found to be at a slightly lower frequency. There is also a small delay associated with the discrete-time control.

This makes the rig entirely suitable for elementary investigation of PID control. In open loop the plant is marginally stable - with a suitable voltage increment the head will traverse from one endstop to the other. But P-only control renders the system stable with simple second order dynamics. Students are asked to introduce sine waves with various frequencies as set-point demands and compare the response with what they have learnt about the Bode plots of second order systems. With higher proportional control the response becomes oscillatory. Students investigate the effects of derivative action to reduce oscillation with faster closed-loop responses. It is slightly more challenging to demonstrate the effects of integral action as the complementary sensitivity has a steady state gain of 0dB. One possibility is to investigate the closed-loop response to speed rather than position demands.

In fact the printer exhibits fairly severe nonlinearities which can largely be ascribed to the use of voltage control rather than current control. This is self-imposed by the functionality of the ELVIS daughter board and counter to the recommendations of [5]. Specifically the response exhibits severe backlash. Students are asked to observe and comment on the symptoms of nonlinearity - both with step responses and with frequency responses. Paradoxically, the nonlinearity allows the benefits of integral action to be more readily observed as the head can “stick” a long way from its set point with P-only or PD control.

In the academic year 2010-2011 students performed two three-hour labs. In the first they investigated both the open-loop response and the closed-loop response with P-only and PI control. They also collected sine wave response data which they used to construct Bode plots as part of marked coursework completed in their own time. In the second lab they investigated PD control, PID control and also the use of dither to overcome the nonlinearity. Both labs received positive (but not outstanding) feedback from students (Table 1). It was felt that two laboratories were excessive; in addition anecdotal evidence suggested students did not enjoy the extensive data analysis associated with the coursework. For these reasons, in the academic year 2011-2012 students performed only one three-hour lab. They were asked to: examine large and small voltage step responses in open-loop; investigate step responses in closed-loop with P-only (both low and high gain), PD, and PID control; investigate frequency response in closed-loop with P-only, PD and PID control. The only marked component was a brief questionnaire to be completed at the end of the three hour lab. A similar lab is proposed for 2012-2013 (at the time of writing), but see Section 3.3 for software changes to the laboratory that considerably reduce the nonlinear effects.

3 Rig development

3.1 Fourth year team project

The original aim of the fourth year team project that ran in the academic year 2008-2009 was to overhaul our practical control laboratories across the spectrum of undergraduate and masters projects. To this end a number of prototype laboratory rigs were built and tested - the printer lab was just one of these. The students quickly identified lack of a suitable all-purpose data

Did you find ...	Yes very	Yes somewhat	Neutral	Not very	Not at all
the PI Lab interesting:	40	50	26	3	0
the PI Lab useful:	52	47	17	3	0
the PID lab interesting:	36	51	25	1	1
the PID lab useful:	34	44	31	2	2

Table 1: Survey of interest and usefulness of practical laboratories in academic year 2010-2011. The survey was taken at the time of the second laboratory.

interface as a major stumbling block to a coordinated approach to developing laboratories. In the words of their report :

“As can be seen from the analysis of the existing laboratory equipment, there are a wide range of systems which each have their own custom interface for signal conditioning and power amplification. Unfortunately, these interface boxes are lacking documentation and are thus difficult to maintain, which means that in order to interface low level signals from a data acquisition system with the equipment, the interface boxes would ideally be redesigned and documented. An alternative is to develop a multipurpose interface which is capable of connecting to and driving all of the equipment in the laboratory. This option was selected as it reduced the amount of work that would have been required to design many similar but subtly different systems and meant that more time could be spent developing and documenting one interface that has the capability to be used with all the equipment in the laboratory.” [7]

To this end a multipurpose interface was designed and its prototype built. It took the form of a daughterboard that sits on an ELVIS II board (Fig 2). Its functionality is shown in Fig 4. It can accept as input several digital and analogue voltage and current signals of various magnitudes and formats. Similarly it is able to supply analogue, digital and PWM drive signals at currents up to 4A and 24V.

Two of the students involved in the team project remained at Manchester to study for PhDs. In that time some small modifications were made to the design and ten copies were built. As it has turned out the boards have not been used for any other experiments. In this sense they are at once over-engineered (most of their functionality has not been used: this is discussed further in Section 3.2.2) and to an extent inappropriate (they are unsuitable

Figure 4: Functionality of the ELVIS II daughterboard: taken from [7].

for supplying current control: this is discussed further in Section 3.4).

3.2 Hardware modifications

The School of Electrical and Electronic Engineering has a policy of encouraging students to work as interns for eight weeks over the summer. Positions are offered competitively and paid for from a variety of sources. In the case of the undergraduate printer laboratories to-date two undergraduates have made significant enhancements to the rig. We discuss each in turn. In general projects that combine control systems understanding with either electronics or software skills hold most appeal for our students. Both projects illustrate this well.

3.2.1 Internship one

In the first year we used the rig for undergraduate laboratories the encoder strip was not used for head position measurement: instead an analogue signal

was obtained using a strip of resistive wire. Although this is more in keeping with the continuous-time methods taught in the course it is a step back from the aim of closely emulating a practical control loop. In the summer of 2011 a student modified the system to accept digital position measurement.

On the printer itself control is undertaken by a microcontroller that receives positional and directional data from an optical encoder and then generates a suitable drive signal for the motor. The positional sensor utilized is an optical quadrature encoder, in combination with an optical strip. The encoder strip is mounted to the chassis of the printer and the quadrature encoder is mounted inside the print head. The encoder outputs a train of digital pulses on its two outputs as it is moved along the encoder strip. The number of pulses is counted in order to determine the position of the print head. The direction of movement is determined by comparing the transition pattern of the two pulse trains. In order to emulate this the routing through the daughterboard was modified to accept the digital signal. The LabVIEW virtual instrument was then rewritten to interpret the digital signal.

The modifications were used successfully for the academic year 2011-2012. New printers were bought (at negligible expense) rather than make any attempt to re-modify the originals. There were two major benefits:

- The sensor noise was considerably reduced.
- The printer hardware was more robust and required less maintenance over the teaching semester.

3.2.2 Internship two

As discussed above, the ELVIS II daughterboard has considerable redundancy for the specific laboratory. In the summer of 2012 we examined the possibility of a leaner solution. In particular, all our first year undergraduate students are given a National Instrument myDAQ board – see (<http://www.eee.manchester.ac.uk/undergraduate/courses/projectwork/mydaq/index.html>). It would be natural to integrate this into the Control Systems I laboratory.

To this purpose a second student worked as an intern over the summer of 2012. He designed and built a working prototype of just such a board (Figs 5 and 6).

The prototype board has no optical isolation. At the time of writing we have designed a modified board but have not yet built the corresponding

Figure 5: Prototype daughterboard for use with National Instruments my-DAQ.

Figure 6: Printer controlled using National Instruments myDAQ and prototype daughterboard with suitably modified LabVIEW virtual instrument.

prototype. Our intention is to use this for the academic year 2013-2014.

3.3 Nonlinearity compensation

The printer head response is highly nonlinear (see for example Fig 3). The taught component of the course is focused on linear responses. In the laboratory we ask students to observe and comment on behaviour that does not appear linear. Nevertheless we would prefer to remove nonlinearities wherever possible.

The nonlinearity itself can be well characterised as a backlash [8]: see Fig 7. It is then possible to use inverse techniques such as those proposed in [12]. The inverse includes discontinuities which in some cases results in actuator chattering. This, however, is overcome using a spatial regularization technique similar to those explained in [4]. This has been successfully implemented (Fig 8) and will be used for the undergraduate laboratory sessions for the academic year 2012-2013.

In addition we have shown that the series combination of backlash inverse, saturation and backlash is itself a saturation function. This allows novel and effective antiwindup and model predictive control techniques to be implemented on systems that exhibit backlash and actuator saturation [9, 10]. The conference paper [9] included a simulation of the printer head system. We have subsequently demonstrated that it also works in practice and have included hardware results in a journal version (currently under review). Similarly we propose to implement and confirm the findings of [10] on the hardware before journal submission.

3.4 Future developments

Although the backlash inverse provides a simple and perhaps surprisingly effective counter to the nonlinearities of the printer device, a more elegant solution might be to use current control [5]. Unfortunately this is not straightforward to implement on either the ELVIS II daughterboard nor the myDAQ daughterboard. We propose to employ a third summer intern to investigate whether such a solution is effective on the rig and can be implemented using a simple daughterboard.

Figure 7: Input-output characteristic of the printerhead showing backlash.

Figure 8: Input-output characteristic of the printerhead with backlash inverse: the effective response is almost linear.

4 Conclusion

We have discussed a laboratory rig that is in its third year of use in Control System I, a large undergraduate class at Manchester. It has been designed and developed by our students themselves. Furthermore it has been enhanced year-on-year, again with the design and development undertaken by our students. This ensures it is directly relevant to, and interesting for, our current cohort of undergraduate students. The design and development has required skills in electronics and real-time software, as well as control engineering. A key feature of the laboratory is its versatility. We plan further changes over the short term and envisage that it will continue to be used for several years - it is easy to update and modify.

Acknowledgements

The authors have recieved considerable support from a number of colleagues both at the University of Manchester and at National Instruments. They would particularly like to thank Hannah Wade at National Instruments for her help and advice.

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