Evaluation and demonstration of take home laboratory kit

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Abstract: This paper discusses some of the reasons for producing take home laboratory kits. This is then supplemented by detailed presentation of three different types of take home kit, alongside the motivations for their design and an evaluation of their efficacy with students.

Keywords: Automated assessment, software tools in control, student expectations.

1. INTRODUCTION

This paper is focussed on laboratory provision within the context of systems and control engineering. However, as the focus is on a demonstration session, we will not use space marking arguments for the inclusion of laboratories into engineering curricula and take these as read (Abdulwahed, 2010). Instead we will focus on the concept of *take home laboratories* (Durfee et al., 2004; Stark et al., 2013) and more specifically on the description and evaluation of three low cost alternatives that have recently been produced.

A core obstacle to the inclusion of hardware in engineering curricula is the combination of timetabling and space; laboratories are expensive to provide and thus are limited in general and this in turn means students have limited access. One popular solution to this dichotomy that has proved very popular in recent years is to increase the use of web base materials (Rossiter et al., 2007b), or more specifically, web based laboratories (Cameron, 2009; de la Torre et al., 2013; Goodwin et al., 2011; Rossiter., 2017). Activities available via the web may, in principle, be available 24/7 and thus not subject to either number, space or time restrictions. However, with the exception of remote access laboratories which themselves are subject to a number of challenges (Rossiter et al., 2014, 2018), remote access activities tend to be based on virtual/mathematical environments and thus are only pseudo-authentic.

Ideally staff would like students to spend more time with hardware and thus the most obvious solution to this is to provide hardware the students can take home and use on their home computing devices. Some obvious advantages of this are:

(1) Students can repeat and modify parameters and tests as often as they need to without the time pressure of a timetabled laboratory.
(2) Students have more flexibility and time to be creative and ask *what if* questions.
(3) Depending on the flexibility of the laboratory, they can code and perform tests outside of tightly defined learning outcomes which also means they have potential for open-ended assignments.

Of course, for these benefits to accrue, the hardware must be user friendly, so some base requirements for the hardware are:

(1) Ideally hardware should be largely plug and play, for example through a USB input port and standard software available to the student (e.g. LabVIEW/MATLAB).
(2) Code templates should be provided and straightforward to edit so that students can implement their own tests.
(3) Support resources should be sufficiently high quality that students do not need *hand-holding* such as may occur in a conventional laboratory.

This paper will present three examples of take home kit being used in the authors' department. Two of these were initially designed and built in-house whereas the latter alternative was produced in the USA.

2. TAKE HOME EMBEDDED CONTROL UNIT

This equipment is used by the University of Sheffield to teach a range of concepts in embedded systems to third/fourth year undergraduate and postgraduate students. It is a low cost (approximately £50) off-the-shelf development board (STM32F4Discovery) incorporating an ARM 32-bit processor and numerous peripherals. It is programmed and powered directly from a computers USB port. An ARM processor is chosen due to its wide use in industrial applications such as Control Systems and Internet-of-Things.

2.1 Equipment outline

The board is built around an ARM Cortex-M4 microcontroller that can be clocked up to 168MHz and incorporates

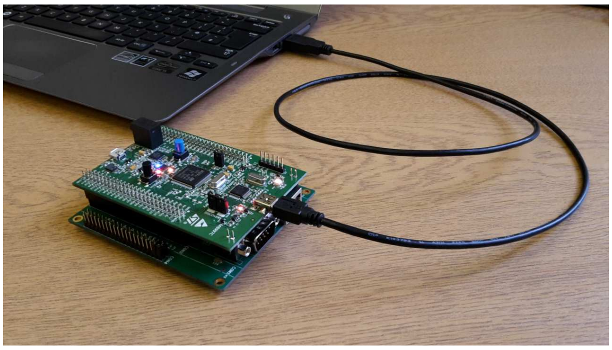

Fig. 1. Take home embedded systems equipment.

a range of functionality, including flash memory, floating point unit, DAC/ADC and support for several standard communication protocols, such as SPI and I2C. The board also contains several external peripherals, including a tri-axial accelerator, push-button, programmable LED's and audio driver. These peripherals allow standard concepts to be tested and simple embedded devices to be developed. All of the microcontroller pins are also available on the board through two DIL pin outputs, allowing more advanced projects to be built. The lab kit is programmed in C. Several compilers and code development environments support the STM32F4Discovery. At the moment Sheffield is using Keil μvision due to its use in industry.

2.2 Student use

Following an introduction, the module covers processor and system architecture, standard communication protocols, software and hardware control mechanisms (such as interrupts) and real-time operating systems. The teaching includes several lectures covering the theory and self-contained lab sheets linking into each lecture. The lab sheets cover both simple steps/processes and also "mini-projects". All of the material is available at the start of the module, allowing students to work in their own time and ahead if desired and each lab sheet is supported through timetabled lab-sessions. Online tutorials have also been used over the past couple of years to provide additional support without the requirement for bookable lab space. Assessment of the module includes labs assessing basic practical knowledge, an open book test linking in-part to the labs and primarily assessing the theory, and a final assignment. The final assignment assesses both theory and practical knowledge and to achieve the higher mark range, requires students to apply their knowledge and skills to solve a more complex unfamiliar problem.

2.3 Main challenges in use

As the lab kit is used in advanced level modules it requires previous experience in C programming and basic embedded systems. In terms of student satisfaction, this has caused problems with some students whose programming knowledge is weak, or are forced to take the module as a core requirement. In terms of delivery, the main challenges relate to both supporting students learning and assessment. The students cohorts are usually in excess of 100, which means that graduate teaching assistants (GTA's) are extensively used. However, as ability to support students and debug problems easily and quickly is proportional to the amount of time spent using the equipment, rotation of GTA's every few years and the limited preparation time that they have available each year, still means that the main module teaching staff need to be involved and available during all lab sessions. Closely linking teaching and assessment to the practical work also means that these staff need to be available at times outside of the scheduled sessions to support students with "operational" issues with their lab kit. Finally, reliance on fixed lab kit also means assessment needs to be carefully planned so that critical information is not available to students through feedback, creating problems when setting assessment for future cohorts.

3. TAKE HOME HELICOPTER EMULATOR

This equipment was designed and built within the Department of Automatic Control and Systems Engineering at the University of Sheffield. The design brief was to develop an engaging, yet low cost and portable system that could be loaned to each student for the duration of a semester, in order to better support the teaching of advanced control and systems engineering concepts. The portable aspect of the kits, in particular, enables students to conduct practicals in a time and place of their choosing, freeing them from the constraints of conventional teaching laboratories.

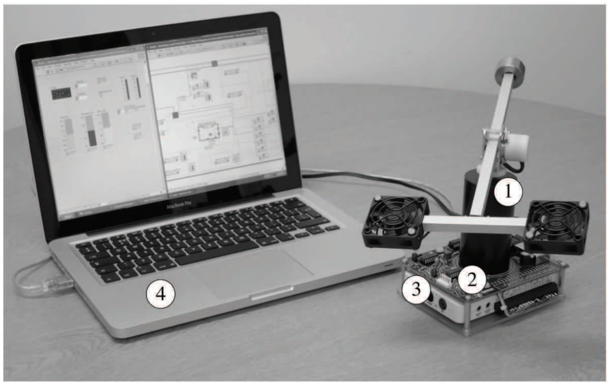

Fig. 2. Take home helicopter equipment.

3.1 Equipment outline

The take-home kits consist of a mechanical linkage that can pivot separately about three axes in response to the thrust produced by two separate fan actuators. Each axis is equipped with a sensor to measure angular rotation. The system is therefore multivariable, and possesses a range of nonlinear dynamics, making this a challenging system to control. The mechanical linkage is separable from an electronics interface board via a D-type connector. The interface board hosts the necessary circuitry to power the fans and route signals to a National Instruments MyDAQ, which sits below the board and relays control and sensor signals to a PC via a standard USB cable. The separable nature of the linkage and associated electronics enables storage within a small toolbox, which students use to transport the kit between home and campus. Also contained in the toolbox are a rudimentary I/O board and an individual fan board consisting of a single fan (the same as used on the linkage) mounted on a strain-gauge sensor. Both boards again interface to the main electronics board via a D-type connector.

Learning outcomes supported by the equipment include:

(1) Data-acquisition and control.
(2) Modelling and simulation of multi-physics systems.
(3) System identification.
(4) Multivariable control and state estimation.

The data-acquisition and control tasks are programmed in NI LabVIEW, whilst the modelling, simulation and control design tasks are conducted in Matlab/Simulink. The rudimentary I/O board is used to teach students the basics of data acquisition and control, whilst the fan module supports a system-identification experiment that enables students to construct a model of the fan dynamics. A series of experiments upon the mechanical linkage then allows students to parameterise the equations of motion for the mechanical system that are derived from first-principles. After validating their simulation models against the actual hardware, students are tasked with designing a reference tracking feedback controller capable of tracking constant reference signals with zero steady-state offset. This is tested upon the simulation model before being imported into LabVIEW for actual implementation. LabVIEW and Matlab code templates are provided throughout.

3.2 Main challenges in usage

Although Matlab is familiar to the students, the same is less true of LabVIEW. Therefore, the early lab sessions are devoted to up-skilling students in this language, with particular emphasis on the data-acquisition and control aspects. Campus-wide software licenses are available for Matlab and LabVIEW, although the latter's support for MACs has lagged behind the former's, and successful usage of the software does rely upon students reading installation instructions carefully, which each year proves to be beyond the capabilities of some. Logistically, the module benefits from access to PC laboratories with sufficient capacity to host the required number of students. Even when the student cohort is divided into two groups, access to such a resource is a constant challenge. These labs are timetabled to enable students to access GTA support and have their exercises ticked-off once completed.

3.3 Student usage

This equipment is used to support two-different modules. The first is a module delivered to third-year undergraduate students from a range of different engineering departments, whilst the second is delivered in a two-week intensive period to MSc students. All students possess the core prerequisite knowledge of state-space control. The student feedback is overwhelmingly positive and with student numbers limited by the numbers of available kits, each year there are significant numbers of students who are unfortunately turned away.

4. TEMPERATURE CONTROL LAB KIT

The temperature control lab (TCLab) is an application of feedback control with an Arduino, an LED, two heaters, and two temperature sensors as shown in Figure 3.

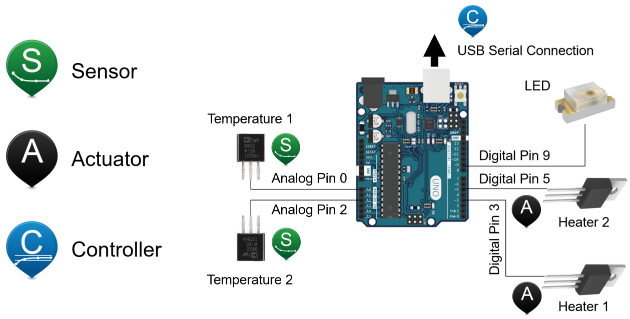

Fig. 3. Temperature sensors and heater actuators with connections to an Arduino.

The heater power output is adjusted to maintain a desired temperature setpoint. Thermal energy from the heater is transferred by conduction, convection, and radiation to the surroundings and to the temperature sensor. This lab is a resource for model identification and controller development. It is a pocket-sized lab with software in Python, MATLAB, and Simulink for the purpose of reinforcing basic and advanced control theory with applications in modeling, estimation, and control (Hedengren et al., 2014).

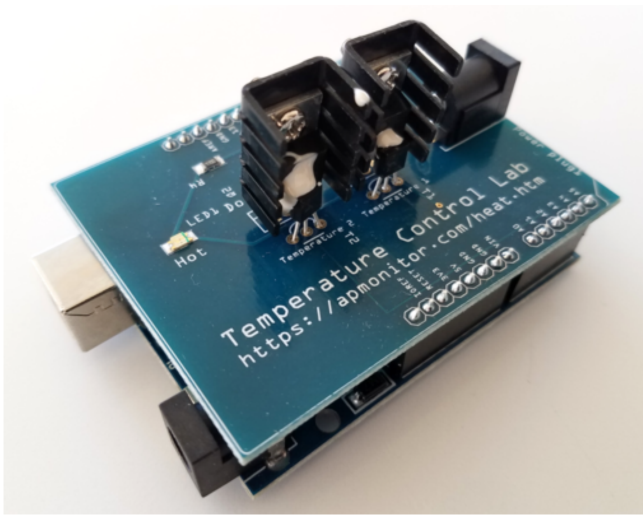

Fig. 4. Pocket-sized process control lab.

The module shown in Figure 4 was developed at Brigham Young University (Hedengren, 2019) in response to the 2015 US National Science Foundation (NSF) report "Chemical Engineering Academia-Industry Alignment: Expectations about New Graduates" (Luo et al., 2015). The report identifies a strong industrial need for practical understanding of process control and system dynamics. Industry feedback also suggests more weight on translating process control theory to practice. The pocket-sized process control lab reinforces process control theory as a take-home lab. The open source, small (3" x 2" x 5"), and inexpensive (27) process control kit is given to students to reinforce concepts in dynamics and control theory. Lab kits have been distributed to early-adopting universities that include Notre Dame, Iowa State, Oklahoma State, Georgia Tech, New York University, Louisiana Tech, McMaster University, Christian Brothers University, Villanova, University of Iowa, Brigham Young University, University of Pretoria, Western Michigan University, and Zaragoza

University. Companies such as APCO, Inc. have developed commercial software for the TCLab into SimTune for training on industrial controllers such as Allen Bradley and Honeywell PID control (SimTune, 2019). University instructors share open access teaching resources that reinforce topics such as:

(1) Step and doublet testing.
(2) First order (time constant, gain, and dead-time) and energy balance models as shown in Figure 5.
(3) On-off control.
(4) Simple feedback structures such as PID (see Figure 6).
(5) Feedforward and cascade control.
(6) Higher order modelling.
(7) Machine learning.
(8) Relative gain array pairing.
(9) Stability analysis.
(10) Advanced modelling techniques (e.g. recursive least squares) and state estimation.
(11) Multivariable control.

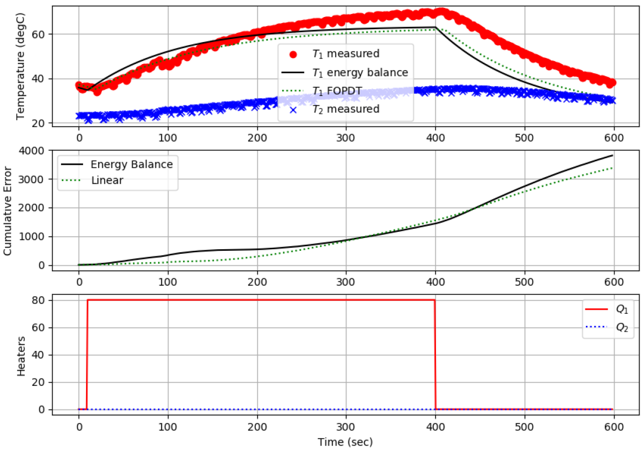

Fig. 5. Empirical first order and energy balance model performace.

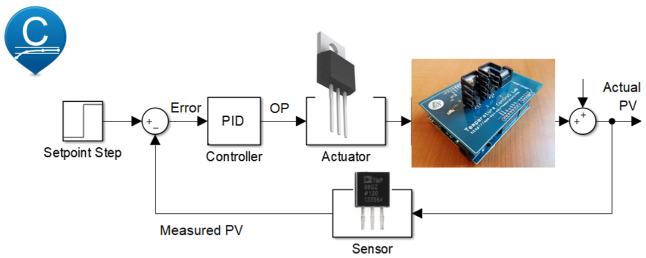

Fig. 6. PID control with the TCLab in Simulink.

The equipment plugs directly into the USB port of a computer and has a separate power source, again taken from a standard USB power unit. The USB power supply should not taken directly from a computer USB 2.0 port as this does not supply enough current. A USB 3.0 or USB C port does supply sufficient current but the heater pulse width modulation (PWM) causes a fluctuation in supply voltage that produces noise for the temperature readings. Using the 5V, 2A power supply for the heaters is recommended.

4.1 Equipment outline

In brief, the system is a simple multivariable system with 2 inputs (heating power to two separate heaters) and 2 outputs (temperature measurements at two different points). The characteristics are close to first order and thus ideal for supporting the learning of introductory dynamics and feedback. Also, the interaction is mild enough so that SISO control is effective while significant enough to be noticeable and thus form an introduction to multivariable issues.

MATLAB and Python GEKKO Beal et al. (2018) code templates are provided for many of the obvious learning outcomes so that students do not need to be proficient programmers in order to implement any changes and experiment designs to suit their own needs. They do of course need to know elementary MATLAB/Simulink and/or Python, but by elementary we really do mean just 5-10 hours experience so that there is an understanding of variables and loops. More details, video instructions, resources and so forth are available at:

- Overview: http://apmonitor.com/heat.htm
- Python Package: https://pypi.org/project/tclab
- Control Design: https://youtu.be/Mbx5IMICS_Y
- Advanced Control: https://bit.ly/2DcyBWl

4.2 Main challenges in usage

The students in the authors' department are comfortable with MATLAB but do not know Python. As the equipment includes an Arduino, it is necessary to add the Arduino toolbox to the MATLAB search path and therefore this toolbox needs to be downloaded.

- For an ideal plug and play scenario the required Arduino toolbox should be available on university networked machines. However, as this Arduino toolbox is provided by an independent party and not MathWorks, it is not included on the university computer system MATLAB implementation. It took significant discussions with MathWorks staff and some ingenuity to find a work around that is satisfactory on the Sheffield network, but even this requires students to do a manual setpath statement to an obscure directory each time to make the hardware work.
- Students wishing to use the hardware on their personal computers would need to install the Arduino toolbox themselves and this may require software skills beyond expectations for the cohort at the place in the curriculum where the hardware is most wanted.

Another obstacle is that the power supply components provided by the supplier do not meet UK safety standards (US power supply with a UK plug converter) and thus had to be replaced with a single 5V USB UK power supply. Figure 7 shows the replacement power module. Also, the underlying Arduino unit has many electrical terminals exposed which could increase danger of shorts if placed on the wrong surface; technical staff in the authors' department decided this should be shielded with a perspex block.

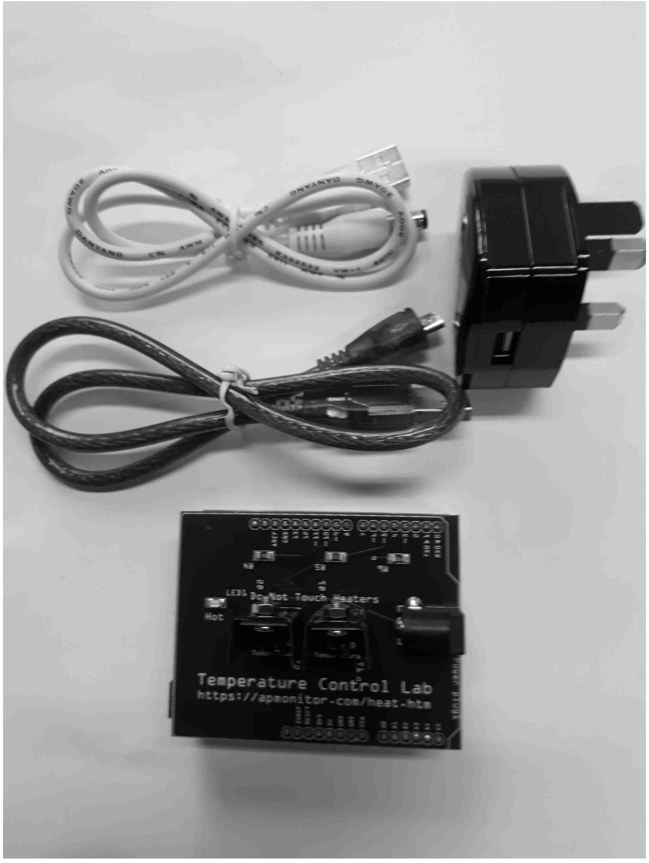

Fig. 7. Take home temperature control laboratory.

4.3 Student usage and evaluation

The equipment has been used with two distinct cohorts. Although a formal evaluation was not undertaken as the use of take home laboratories in general is now comman place in the main author's departement, a summary of anecdotal comments from students and staff observations is appropriate.

Some second year chemical engineers, who have minimal MATLAB competence, used the equipment as part of a poster assignment where the hardware was used to produce evidence of different learning outcomes. Not much was demanded of this cohort and a simple modelling demonstration followed by some PID tuning would have been sufficient, but some students thrived on the opportunity and managed to perform state estimation and predictive control. However, it was clear that, in general this cohort needs much more support with the programming side in order to get the most from the equipment and struggled to self teach the core programming skills they needed. This is likely a reflection of the lack of programming elsewhere in their programme prior to this point.

The 2nd cohort (2nd year general engineering students) mastered the equipment better, perhaps because their background meant that they were more comfortable interacting with the MATLAB programmes supplied and self-learning the addtional programming aspects they needed. Indeed, the main comment from this cohort that is relevant is that many of them found the take home project gave them much more interest in and enthusiasm for control topics in general.

5. CONCLUSION

Staff in the authors' department first started active consideration of take home laboratories about 6 years ago. Having begun with designs that were produced in-house, this year they have also tried an example produced elsewhere. In all cases they have been pleased with the results and student engagement with the hardware. From a cost perspective, compared to the cost of providing laboratory space, support staff and robust laboratory equipment (often 5-10K per item), the take home alternatives are very cheap, ranging in price from 40-400 per item but notably without the requirement for expensive laboratory space.

In terms of staff elsewhere adopting take home laboratories, the most valuable lessons learned are the same as those stated in the introduction: (i) kit must ideally be plug and play via a USB port and readily available software; (ii) support resources should be high quality enough to avoid the need for frequent assistance; (iii) code templates should be editable so that students can explore their own ideas.

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