Control-Lab-in-a-Box: Bridging the Gap between Control Theory and Engineering Practice

Pickering, James[a]

Aston University, Birmingham, UK[a]

Corresponding Author's Email: j.pickering1@aston.ac.uk

KEY WORDS: Control engineering; mathematics; engineering practice; lab-in-a-box; MATLAB and Simulink

SUMMARY

Traditional control engineering teaching methods heavily rely on abstract mathematical concepts, often leaving students puzzled about real-world applications. Common simulation tools, such as MATLAB and Simulink provide a good visual demonstration but don't necessarily bridge the gap between theory and application. The proposed 'lab-in-a-box' approach offers a tangible method for students to connect control theory with a practical control engineering experience. The literature has observed a shift towards such portable labs, given the advancements in compact computing devices such as Raspberry Pi and Arduino boards in electronics and control teaching. The primary goal of these labs is to deliver an authentic engineering experience with essential hardware. Evaluation of this method, through the student module evaluation questionnaire (MEQ), revealed a significant increase in student satisfaction after its introduction. While the results are promising, challenges remain, such as the initial set-up of the kits. However, the 'lab-in-a-box' is found to be a valuable tool in control engineering education, bridging the gap between theoretical and practical understanding. An on-going development includes updating of the kits to match future engineering challenges and needs, e.g., electrification and autonomy of vehicles.

INTRODUCTION

The traditional methods of teaching control engineering with abstract mathematical concepts (control theory) often leaves students grappling to connect theoretical knowledge with practical control applications. This presents a challenging question: How do educators ensure that students leave University understanding the connection between control theory and practical control applications.

The practice of supporting the teaching of control engineering often relies heavily on the use of simulation tools such as MATLAB and Simulink, with the tools well received in helping to understand the mathematics. However, when students question the real-world relevance of what they're learning, a mere visual demonstration in lectures might not suffice. Even hands-on robotic demonstrations can inadvertently obfuscate learning if not handled with care, as these demonstrations can be too advanced for early learners of the topics.

The ‘lab-in-a-box' introduced in this paper provides students’ with a portable set of labs. The labs allow student to demystify the divide between theoretical concepts (control theory) and practical applications. The ‘lab-in-a-box’ is especially useful at allowing students to visualise control theory being used in practice, i.e., significantly enhancing the learning experience. This approach can complement the traditional teaching methods and provide students with an enhanced understanding of control engineering.

LITERATURE REVIEW

In the current control engineering academic world, see (Rossiter, 2020), there are controversial views regarding creating a first course with reduced mathematics. Rossiter (2022a) states that students in engineering tend to over-associate ‘control’ with ‘mathematics’ and under-associate with how a control system operates. In parallel, with the demise of traditional laboratory facilities in academia, there has been an increase in the use of smaller portable laboratory systems, see (Stark et al., 2013), (Taylor, Jones, and Eastwood, 2013), (Oliveira and Hedengren, 2019), (Vargová et al., 2023), (Takács et al., 2024) and (Takács et al., 2024). These developments have become feasible due to advancements in compact microprocessors/microcontrollers, notably through devices such as the Raspberry Pi and Arduino boards (Hedengren, 2019). The primary objective has been to offer students uninterrupted access to an engineering experience using hardware. Rossiter (2022b) offered the following definition:

i. "Take home" refers to equipment that is portable, affordable, lightweight, easily integrated with a student's laptop, and available in large quantities, allowing an entire class of students to borrow it for extended periods.
ii. It's assumed that any necessary software (e.g., LabVIEW, MATLAB and Python) is either freely available or provided under an institutional license. Additionally, the lab equipment should easily connect to a laptop, preferably via a USB or a similar straightforward connection.

iii. Any associated risk assessment, which is mandatory, should indicate a very low level of risk.

THE ENGINEERING EDUCATION PROBLEM AND INTERVENTION

From the author's own early experiences teaching control engineering, students frequently posed the question: "How does this theory relate to real-world applications?" One initial approach was to incorporate visual examples of control system applications within lectures. However, this sometimes introduced more confusion due to not understanding the details of the application (e.g., electronics and software) or simply that the complexity of the example was really too great for entry-level teaching of the subject. Another strategy involved incorporating hands-on demonstrations during lectures, using tools such as Quanser equipment or robotic examples. Yet, this too could muddle understanding, especially if students struggled with grasping the electronics and specific control methods used. Additionally, many modern educational robotics kits use black box control algorithm design methods, which don't effectively serve as great educational tools. Based on the experience of the author, the gap between theoretical and practical teaching of control engineering is large and this can often lead to major misunderstandings.

To bridge this theoretical-practical divide, the author introduced the 'lab-in-a-box' concept into the classroom. These kits were equipped with a microcontroller and various electronic and mechanical components. Designed for portability, students could utilise these labs at their convenience. Based on the fact that students' had already been taught the theoretical topics (i.e., control theory, electronics, and mechanical systems), these labs allowed the students' to demystify the practical aspects of control engineering. The labs incorporated auto-code generation through MATLAB and Simulink, thereby providing a natural flow from the teaching of theoretical concepts through to control algorithm design (software) onboard a microcontroller. Using such a package also allows students' to view signals in real-time.

DESCRIPTION OF PRACTICE

Table I provides details of the teaching programme that the author has developed since 2016, with the aim to bridge the gaps between theory, simulation, and practice. Control engineering is traditionally taught using mathematical concepts, such as continuous-time and discrete-time mathematics, along with a simulation tool (e.g., MATLAB and Simulink) in both the design and analysis of closed-loop control systems.

Prior to this teaching programme, it is assumed that students already have a 'sound' understanding of mathematics and electrical science. In the continuous-time teaching (left-hand column of Table I), it is important to state in Lecture one and continuously remind students' throughout the course that the subject wont 'click-in place' until the whole teaching programme has been undertaken. This is due to the nature of the subject – with the connection of the various control theory topics becoming clearer week-by-week. For a Mechanical Engineering degree, the content of Table I is taught over a two-year period (e.g., 2^{nd} year (first course) and 3^{rd} year (second course)), with the links between theory, simulation and practice becoming clearer towards the end of the programme. Assessment is via coursework and examination. For the coursework, MATLAB and Simulink virtual labs are used to reinforce learning with a practical application, see (Allie, 2024).

Lab-in-a-box examples are given in Figures 1 to 2 for the following:

i. Temperature sensor, TMP36 with low-pass filter (Figure 1)
ii. Obstacle avoidance using a lab scaled vehicle (Figure 2)

For the above examples, details of the basic set-up are given, i.e., the control theory being used in practice. The Simulink diagram (software design) given in Figure 1 is embedded onto the Arduino Uno microcontroller using auto generation. Simulink allows for students to see signals in real-time, e.g., in Figure 1, unfiltered temperature sensor signal (blue signal) and filtered signal (white signal).

Table 1. Teaching Programme for a Control Engineering First and Second Course: Control Theory, Simulation and Practice for a Mechanical Engineering degree

First course	**Second course**
Theory and Simulation - Continuous time	**Theory and Simulation - Discrete time**
1. Introduction to Control Engineering 2. Introduction to Laplace 3. Transfer Functions 4. Block diagram algebra 5. Inverse Laplace (system response) 6. 1^{st} order system response 7. 2^{nd} order system response 8. Stability and performance 9. Frequency response 10. Proportional control 11. PID control and tuning with applications	1. Introduction to sampled data control system 2. Discrete-time modelling 3. Time-solution 4. Stability and performance 5. System identification 6. PID control and tuning **Practice (Lab-in-a-Box) - Embedded Control** 7. Introduction to microcontrollers 8. Actuators (e.g., DC motor, motor driver and servomotor) 9. Measurement devices (e.g., temperature sensor with low pass filter and ultrasonic sensor) 10. System Identification (e.g., pendulum and RC circuit) 11. PID control and hardware/software-in-the-loop (H/SIL)

Figure 1. Temperature Sensor TMP36 with a Low Pass Filer

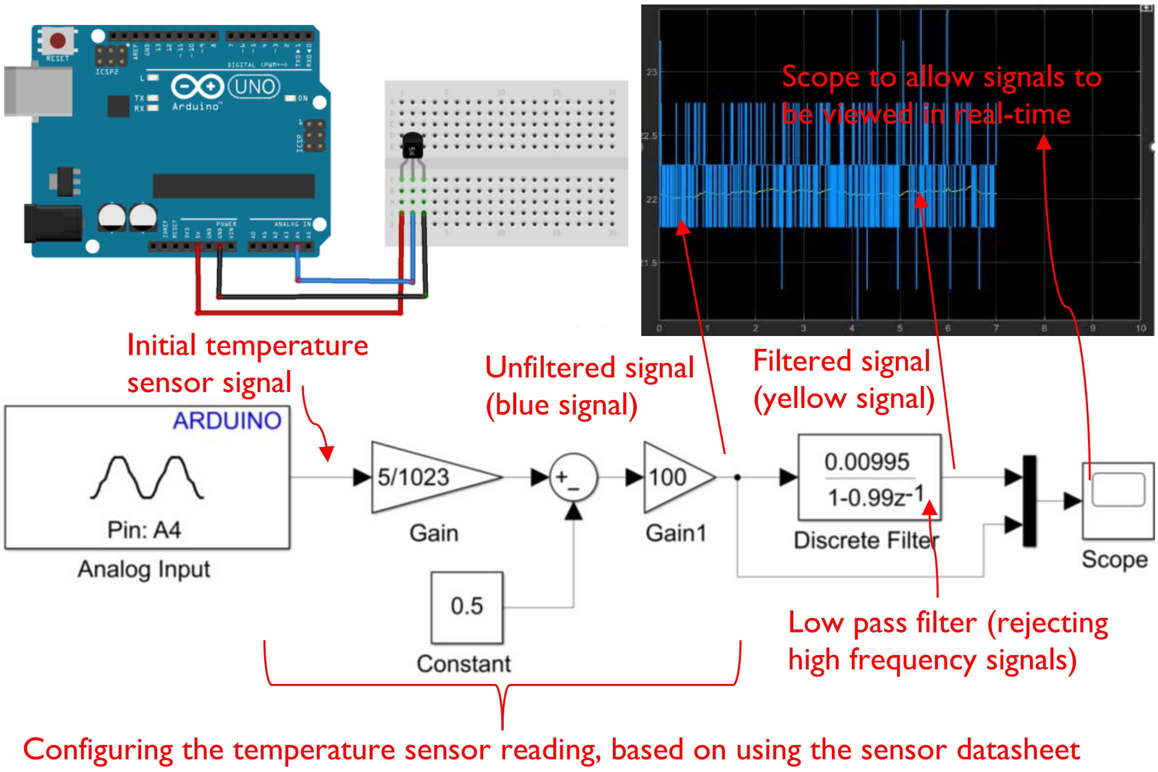
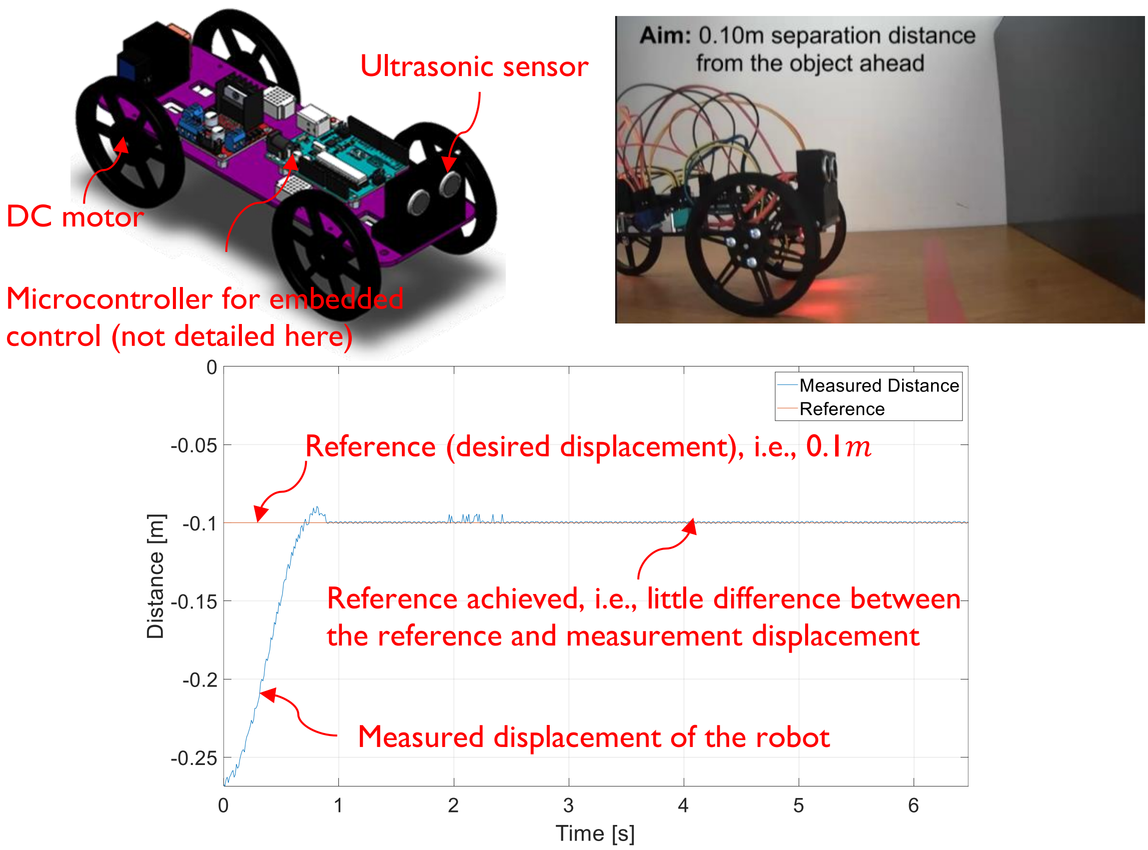


Figure 2. Obstacle Avoidance of a Lab Scaled Vehicle to Stop within 0.1meters of an Object (i.e., Displacement Control of 0.1meters)

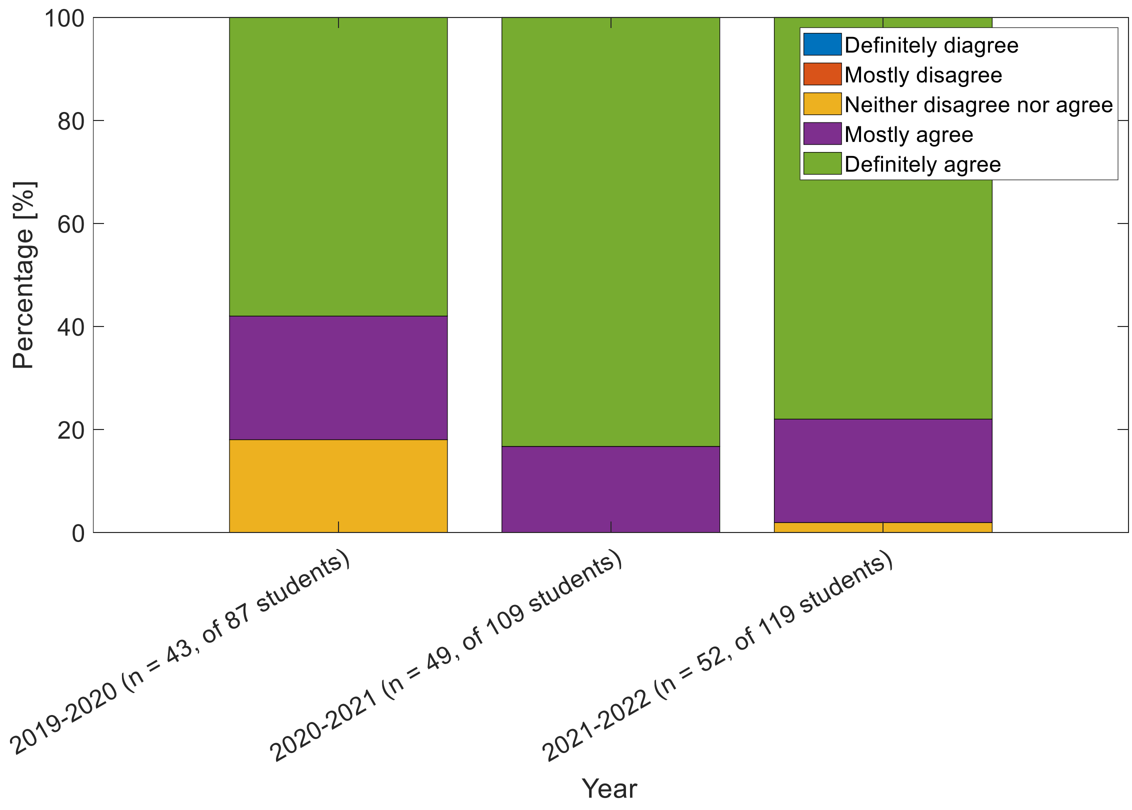


EVALUATION OF PRACTICE

To evaluate the success of the practice, the author has collected evidence extracted from the student module evaluation questionnaire (MEQ) results from 2019 to 2022, see Figure 3. The MEQ consists of 19 questions that purposely align to the National Student Survey (NSS). The results to be presented are based on a 3rd year module where a full cohort of students have been through the process of being taught the material presented in Table 1. Note that the results given in this paper are prior to joining Aston University, when the author was at Coventry University.

As a baseline, prior to the introduction of the 'lab-in-a-box' and based on the question, 'Overall, I am satisfied with the quality of this module', the highest MEQ result for the 3rd year module was 82% (i.e., students answering 'mostly agree' and 'definitely agree') in 2019/2020 (43 out of the 87 students participated in the survey), see Figure 3. Upon introducing the 'lab-in-a-box' in 2020/2021, the 'overall student satisfaction' question result for the MEQ increased to100% (49 out of 109 students participated in the survey) and in 2021/2022, the MEQ result was 98% (52 out of 119 students participated in the survey), see Figure 3.

Figure 3. Module Evaluation Questionnaire (MEQ) Results between 2019 and 2022



DISCUSSION

Following the introduction of the 'lab-in-a-box', the results from the student MEQs present encouraging results. The significant increase in student satisfaction is a testament to the potential of hands-on, practical teaching tools in enhancing the learning experience. Also, based on improved assessment outcomes, these results further reinforce the author's view that when students' directly apply the taught theoretical concepts (control theory) to a practical application, they're better equipped to understand and retain knowledge.

However, there are significant challenges. The initial setup of the kits can be daunting. It is suggested to increase the number of labs within the 'lab-in-a-box' incrementally per year. The 'lab-in-a-box' kit cost is around £70, with this offering a cost-efficient educational experience. Once set-up, only replacement parts each year are required (with this being at a low cost). Furthermore, educators must ensure that the exercises and labs align with the course's learning objectives (subject to course accreditation with the relevant professional bodies).

CONCLUSIONS & RECOMMENDATIONS

As witnessed by the author, the introduction of the 'lab-in-a-box' approach has provided a significant advancement in both control engineering teaching and learning. Whilst traditional teaching methods provide the necessary foundational knowledge, the developed portable hands-on 'lab-in-a-box' approach ensures that students' grasp a better understanding of the practical implications of theoretical concepts. Future research will focus on refining the kit's contents and aligning them more closely with evolving curricular needs, e.g., electrification and autonomy of vehicles.

REFERENCES

Allie, C., 2024. Virtual Hardware and Labs for Controls (https://github.com/MathWorks-Teaching-Resources/Virtual-Controls-Laboratory/releases/tag/v2.0.1), GitHub. Retrieved January 24, 2024.

Hedengren, J.D., 2019. Temperature Control Lab Kit, http://apmonitor.com/heat.htm. Retrieved January 24, 2024.

Oliveira, P.M. and Hedengren, J.D., 2019. An APMonitor temperature lab PID control experiment for undergraduate students. In *2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)* (pp. 790-797). IEEE.

Rossiter, A., Serbezov, A., Visioli, A., Žáková, K. and Huba, M., 2020. A survey of international views on a first course in systems and control for engineering undergraduates. *IFAC Journal of Systems and Control*, *13*, p.100092.

Rossiter, J.A., 2022a. Take home laboratories enhancing a threshold approach to assessment. IFAC-PapersOnLine, 55(17), pp.224-229.

Rossiter, J.A., 2022b. Future trends for a first course in control engineering. *Frontiers in Control Engineering*, *3*, p.956665.

Stark, B., Li, Z., Smith, B. and Chen, Y., 2013, August. Take-home mechatronics control labs: A low-cost personal solution and educational assessment. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 55911, p. V004T08A036). American Society of Mechanical Engineers.

Takács, G., Mikuláš, E., Gulan, M., Vargová, A. and Boldocký, J., 2023. Automationshield: an open-source hardware and software initiative for control engineering education. *IFAC-PapersOnLine*, *56*(2), pp.9594-9599.

Takács, G., Mihalík, J., Gulan, M., Vargová, A., Mikuláš, E. and Ožana, Š., 2024. MagnetoShield: A Novel Open-Source Magnetic Levitation Benchmark Device for Mechatronics Education and Research. *Sensors*, *24*(2), p.538.

Taylor, B., Eastwood, P. and Jones, B.L., 2013. Development of a low-cost, portable hardware platform for teaching control and systems theory. *IFAC Proceedings Volumes*, *46*(17), pp.208-213.

Vargová, A., Boldocký, J., Gulan, M., Staroň, M., Mikuláš, E. and Takács, G., 2023. PressureShield: an open-source air pressure pocket lab for control engineering education. In *2023 24th International Conference on Process Control (PC)* (pp. 96-101). IEEE.