Promoting Active Learning of Competences in Control Engineering with Take-Home Maglev Labs

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Abstract: We present a set of potential Intended Learning Outcomes (ILOs) and associated Teaching and Learning Activities (TLAs) for a low-cost, portable, open-source magnetic levitation (maglev) lab designed to support hands-on learning in control engineering. Beyond outlining how this platform can provide students with practical experience, we share insights from our classroom implementation. Specifically, we discuss how the setup aids in intuition development in system modeling, controller design, and stability analysis, along with recommendations for making it engaging and interactive. We also highlight how the lab's reconfigurable nature enables experimentation with different configurations and control strategies, making it suitable for various inquiry-based learning techniques. Finally, we describe how the lab has been integrated into coursework, present student feedback on accessibility and practicality, and report preliminary findings on its effectiveness in promoting self-efficacy.

Keywords: Self-Efficacy in Engineering Education, Reconfigurable Laboratory Platforms, Inquiry-Based Learning, Virtual and Physical Labs, Hands-on Learning

1. INTRODUCTION

Practical experimentation is a cornerstone of engineering education, yet access to laboratory resources remains a challenge for many students. Traditional lab setups are often expensive, space-constrained, and require institutional infrastructure, limiting opportunities for hands-on learning outside designated lab hours. To democratize education and foster active learning, there is a growing need for affordable, portable, and open-ended laboratory platforms that allow students to engage in experiential and inquiry-based learning at their own pace.

Control engineering, in particular, benefits from hands-on experimentation, as many key concepts—such as system dynamics, feedback control, and stability—are inherently abstract and difficult to grasp through theoretical instruction alone. Providing students with the ability to experiment with real physical systems can help develop stronger intuition and practical problem-solving skills, reinforcing theoretical knowledge through direct observation and experimentation. Additionally, hands-on experience has been linked to increased self-efficacy, providing students with the confidence to tackle complex engineering challenges.

To address these needs, we introduce a low-cost, portable, open-source magnetic levitation (maglev) lab specifically designed for hands-on control engineering education. This platform enables students to explore system modeling, controller design, and stability analysis in a tangible and interactive way. Its reconfigurable nature allows for a variety of experimental setups, making it well-suited for inquiry-based learning and encouraging students to actively test hypotheses, analyze results, and refine their understanding of control principles.

Beyond developing a standalone hardware solution, our broader goal is to create an extensible ecosystem of hardware and learning materials that instructors and students can build upon. By sharing open-source resources and structured teaching materials, we aim to make high-quality, hands-on control engineering education accessible to a wider audience, fostering a collaborative environment where learning can be continuously improved and expanded.

In this paper, we present our approach to integrating the maglev lab into coursework, discuss the pedagogical strategies it supports, and share insights from student feedback on its usability and effectiveness in promoting self-efficacy.

Related Work We start this part of the paper with a brief introduction to hands-on learning in Control Engineering. Practical applications have played a critical role in reinforcing theoretical concepts in general (e.g., see Dominik May and Boehringer (2023)), and indeed, laboratory-based learning has long been a cornerstone of engineering education, where hands-on experiences allow students to bridge theory and practice (Garduño-Aparicio et al., 2018). The growing importance of accessible, self-directed learning has led to the development of take-home laboratory kits, which allow for flexible, out-of-class experimentation (Park et al., 2020; Rossiter et al., 2019;

Sotelo et al., 2022), extending the benefits of traditional labs beyond the classroom.

Thus, several authors have focused on creating take-home and DIY laboratory kits, which have gained traction as cost-effective solutions that promote experiential learning in remote or constrained settings (Gya and Bjune, 2021). Low-cost, open-source setups like the AutomationShields initiative – providing control labs as Arduino shields – have demonstrated great potential in making control systems education more accessible (Takács et al., 2023; Vargová et al., 2023a,b). Similar initiatives, such as the Sensor Cube, exemplify how open-source hardware facilitates hands-on learning in sensor data processing (Bleier, 2024).

Such approaches have also been used for project-based learning and for the creation of distributed/remote laboratories. For example, project-based activities, such as those used in autonomous vehicle control at Aston University, have been measured to improve student engagement by applying control algorithms to real-world problems (Pickering, 2024). Hands-on experimentation with take-home hardware and/or software kits has also provided a cost-effective alternative to traditional setups in Durfee et al. (2004) and in Pedroso and Batista (2022). The flexibility of these technology-enabled labs, such as remote or take-home systems, addresses cost and space constraints while offering hands-on experiences critical to learning control systems (Alsaleh et al., 2022).

In general, different setups have been contributing to technological integration in control education: systems such as M2PLab, which combine hardware and software for a comprehensive, learner-centered experience, have been shown to enhance control education by supporting student-driven experimentation (Zhou et al., 2024). Similarly, the Centrifugal Ring Positioner (CRP) allows students to design and control systems, reinforcing core concepts while addressing challenges such as measurement noise (Jordens et al., 2022). The AutomatL@bs Consortium has provided students with remote access to physical control laboratories, allowing them to experience a wider selection of practical problems than otherwise locally available (Dormido et al., 2012; Vargas et al., 2011).

We can thus note an alignment of such works with Challenge-Based Learning (CBL), which emphasizes empowering students to engage with real-world problems and apply their theoretical knowledge practically (Gallagher and Savage, 2023). In addition, we report on initiatives that were aimed at redesigning control courses to address societal challenges (Rossiter et al., 2023). This last-cited paper indeed underscores the need for control theory to be taught with real-world applications in mind (something that our hands-on labs directly support).

We believe that the contribution we are offering is aligned with an idea of the future of Control Education that is widely shared with our colleagues. Especially because recent surveys have emphasized the importance of practical learning experiences in undergraduate courses (Rossiter et al., 2020). Our maglev lab addresses these needs by offering students the opportunity to apply control principles in real-world scenarios. This approach aligns with the broader call for more innovative teaching methods in control education (Rossiter, 2022), moving from traditional lecture-based formats to more interactive and technology-enabled learning.

Statement of contributions Besides presenting the maglev lab that we designed to support hands-on learning in control engineering, we connect its architecture and control capabilities to educational applications that teachers of control-related topics may wish to incorporate in their TLAs. We thus outline how our magnetic levitation lab – from hereon referred to as *Maggy* – can be integrated into coursework to promote active and inquiry-based learning, and report our experience by means of a few key lessons that we believed we learned regarding its effectiveness in learning, and challenges it poses while teaching. We thus offer what we believe are good practices for maximizing the impact of Maggy on the learners. For this purpose, we analyze student feedback on the accessibility, practicality, and potential of the discussed setup for enhancing understanding and self-efficacy in control engineering.

2. EDUCATIONAL OBJECTIVES AND METHODOLOGY

The Intended Learning Outcomes (ILOs) for which we foresee Maggy to be immediately useful are the following ones, where we use Bloom's revised taxonomy Armstrong (2010) as a way of categorizing each ILO. More specifically, we foresee that the most immediate activities involving Maggy may lead the students to be able to:

(1) **Analyze** the dynamic behavior of the magnetic levitation system by deriving its mathematical model from first principles and validating it against experimental data. *(Analyze - Bloom 4)*
(2) **Design** a proportional-derivative (PD) controller for the system, tuning its parameters to achieve desired performance criteria such as overshoot, settling time, and steady-state error. *(Create - Bloom 6)*
(3) **Simulate and compare** the response of the system under different controller designs, assessing stability and performance using root locus and frequency-domain analysis. *(Evaluate - Bloom 5)*
(4) **Implement** a PD controller on the physical maglev setup, experimentally verifying its effectiveness in achieving stable levitation and tracking reference positions. *(Apply - Bloom 3)*
(5) **Critically evaluate** the impact of parameter variations (e.g., sensor noise, actuator saturation) on system stability and propose modifications to improve robustness. *(Evaluate - Bloom 5)*
(6) **Communicate** findings through structured reports or presentations, interpreting experimental results, and justifying design choices using theoretical principles. *(Apply - Bloom 3; Create - Bloom 6)*

Methodologically speaking, the above ILOs come from a few main **pedagogical considerations**, that revolve around our belief that modern classes should emphasize collaborative learning, hands-on engagement, and the development of self-efficacy. We discuss these considerations in the following, to motivate the choices of ILOs.

The ILOs should facilitate teamwork and collaboration We believe that one of the major pedagogical advantages

of using the maglev lab is its capacity to foster teamwork and collaborative problem-solving among students. Engineering education often requires students to participate in projects requiring coordination, task division, and joint decision making. The maglev setup naturally encourages this kind of interaction (especially the ILOs revolving around deriving system models, tuning controllers, and interpreting experimental results). Collaborative learning in such settings has been shown to improve knowledge retention and deepen conceptual understanding, since students are required to explain and justify their reasoning to their peers (Wells, 2002).

The ILOs should aid developing self-efficacy Working with a physical dynamic system may support the development of a concrete understanding of abstract control engineering concepts. Unlike purely simulation-based exercises, a tangible system offers immediate feedback and a real-world context that can reinforce learning, if the ILOs are designed in a favorable way. For this, we propose ILOs that include observing how their theoretical models and controller designs translate into real-world behavior, to aid students in developing a stronger intuition for system dynamics and control strategies.

Eventually, our intended goal is to aid self-efficacy (the belief in one's ability to succeed in specific tasks), which the pedagogical literature claims to play a critical role in student learning and motivation (Pajares, 2012). We anecdotally confirm that self-efficacy seem to be particularly important in persistence in problem-solving, willingness to engage in complex tasks, and overall academic performance - we indeed often noted how some students transitioned from the "I can't do this" to the "I can't do this right now, but give me a day to try it out" when they experienced that "things clicked".

Conscious of this, we tried to develop ILOs that foster self-efficacy in several ways:

- Forcing students to have hands-on experiences that ideally make them see tangible results from their work (especially ILOs that aim at reinforcing their confidence in applying theoretical knowledge).
- Encouraging iterative learning (especially ILOs where students are asked to refine their models and controllers through trial and error, since we believe this promotes resilience and adaptability).
- Helping students recognize their capacity for performing analyses and to do problem-solving (especially ILOs that push for directly comparing experimental outcomes with theoretical predictions).

3. MAGGY AS AN EDUCATIONAL LABORATORY INFRASTRUCTURE

We start this section, dedicated to the latest hardware setup, with a reflection on the role of physical labs in modern education. With the increasing availability of digital and AI-driven educational tools, we believe that the role of physical laboratories in engineering education has to evolve. It is true that simulation-based learning environments offer flexibility and scalability, but they often lack the truly experiential learning opportunities provided by tangible systems. Physical labs, such as the maglev setup, play a crucial role in sustaining extrinsic motivation among students. In informal words, the awe of seeing the magnet levitate and the jokes that the students were making to each other by placing objects on top of the levitating magnet and seeing them fly (e.g., paper mugs, small toys) seem to us invaluable. We think that this aids extrinsic motivation, which is often described as a key factor in student engagement, particularly in structured learning environments (Corno and Mandinach, 1983). In addition, we also note an interesting initiative initiated in Cojan et al. (2024), where the authors aim to increase engagement through activities based on artistic concepts.

3.1 System Overview

The hardware has been redesigned from previous years with the goal of providing reconfigurability, while keeping the systems portability. It is similar to the Magnetoshield systems in Takács et al. (2024), but it has slightly different operations and features (especially the fact that the one proposed here is MIMO and reconfigurable, relying on levitation rather than magnetic suspension). This can be immediately seen in Figures 1 and 2, where one can notice a series of holes that enable different spatial configurations of the electromagnets and permanent magnets (i.e., artificially introduce plants variations with a finite variety of configurations to support different control experiments).

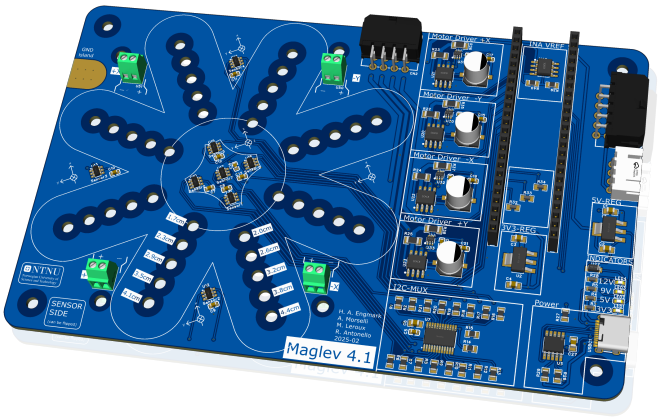

Fig. 1. A rendering of the PCB of the system.

The design philosophy still emphasizes accessibility, cost effectiveness, ease of replication, and has a compact 10×15×5 cm footprint. To increase portability, we switched to a USB-C-based power delivery system.

The main components of the system are its sensors (9 Hall-effect sensors for position sensing; one may select via software different subsets of such sensors, and experiment with how estimation performance may depend on sensor positioning), and the 4 electromagnetic actuators (and note that actually there is the possibility of measuring their currents too, thus allowing us to characterize the dynamics of the actuators).

The micro-controller is still a Teensy 4.1, programmable in C, that was chosen for its balance of cost and performance, providing sufficient computational power for real-time control while remaining affordable.

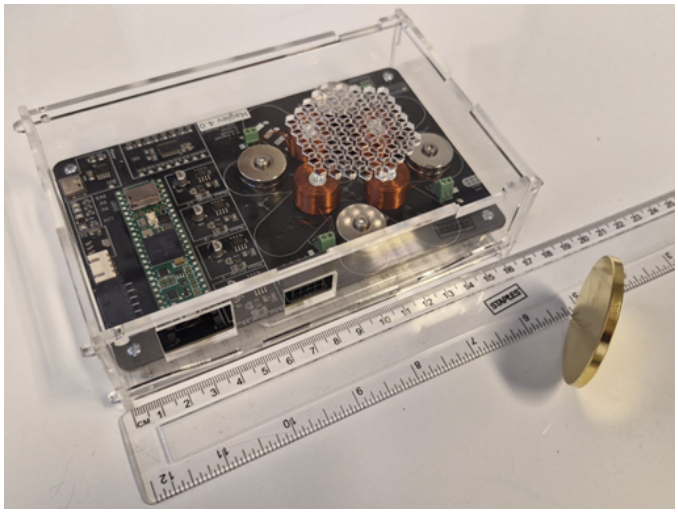

Fig. 2. The setup, together with a ruler to showcase its dimension when embedded in an acrylic box we designed to protect the electronics.

The placement of the Hall-effect sensors is optimized to minimize noise, while students are encouraged to explore filtering techniques to further refine state estimation. Additionally, note that the plant exhibits non-ideality factors such as actuator saturation and electromagnetic interferences (real-life factors that shall be considered in the controller and observer design exercises).

We note that this is an open-source initiative, with all design files, schematics, firmware, hardware schematics, PCB layouts, bill of materials, step-by-step assembly instructions, and software deployment guides available to the broader educational and research community from our GitHub repository [1] . In fact, our goal is to foster a collaborative environment in which the system can be continuously refined and adapted to new educational contexts.

4. EVALUATING THE MAGLEV LAB: STUDENT ENGAGEMENT AND SELF-ASSESSMENT

We now describe and summarize the teaching and learning activities conducted with students at the Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway, in the autumn of 2024. Our goal was to assess how the maglev lab setup supports self-assessment and the development of key control engineering skills. To this end, we designed and tested materials aligned with the following Intended Learning Outcomes (ILOs), somewhat a reduced version of the ones proposed in Section 2:

- **Design** a proportional-derivative (PD) controller for the maglev system, tuning its parameters to achieve desired performance criteria such as overshoot, settling time, and steady-state error. *(Create - Bloom 6)*
- **Critically evaluate** the impact of parameter variations (e.g., sensor noise, actuator saturation) on system stability. *(Evaluate - Bloom 5)*

The designed material was tested in lab activities carried out by students between September 23 and November 11, 2024. The participating students were all enrolled in the second or third year of undergraduate electronics and control engineering programs. The students participated on an optional basis, as the labs were scheduled close to the exam period, and we wanted to avoid overloading students with extra mandatory work. This decision, while respectful of students' schedules, is, from a data-science point of view, a bit dangerous, since it may introduce some self-selection bias in our findings.

We organized students into self-managed groups of four and implemented an A/B study over two weeks. More specifically, group A started with a simulated lab experience in the first week before moving to the physical lab in the second week. Group B followed the reverse order. Each session lasted approximately three hours, allowing students to engage with both virtual and physical implementations of the maglev system.

The virtual lab focused on system modeling, controller design, and simulated responses, while the physical lab emphasized hands-on experimentation, real-world uncertainties, and sensor-actuator interactions. We hence note that the two labs are actually complementing each other; implementing an A/B study was a choice dictated by the intuition that in this way we could measure whether it is best to do "first theory, and then practice" or vice versa.

To measure the impact of the lab activities on self-assessment and learning outcomes, we collected data through a non-mandatory questionnaire where we asked the students their opinions about:

- self-perceived performance based on their ability to design and tune controllers, interpret system behavior, and analyze experimental results.
- challenges they faced, and perceived differences between virtual and physical labs.

The questionnaires were actually two - indeed, students completed one dedicated survey after each session (all Likert-scale questions and open-ended reflections on their confidence in applying control concepts were, though, having the same style). For completeness, the reader may find the questionnaires, as well as more information about Maggy, in our GitHub repository[1].

The qualitative and quantitative feedback from about 80 participating students gave us some key insights. Most notably, the students reported increased engagement when transitioning from the virtual lab to the physical setup, as they could directly observe real-world system behavior and refine their intuition. We note, though, that this feeling was not shared by everybody: some students expressed that starting with the physical lab provided a better grounding for interpreting simulation results (while others found the reverse order beneficial for reinforcing theoretical understanding before experimentation).

Another factor that was often reported by students was that the hands-on aspect of the physical lab was particularly valuable for them in understanding system nonlinearities, sensor noise, and actuator limitations, which were not as evident in the virtual environment.

In any case, and overall, students highlighted that the structured connections that were present in the lab in-

[1] https://github.com/Hansolini/Take-home-Maglev-lab

structions between virtual and physical implementations helped in building confidence in system modeling, controller design, and troubleshooting. These findings provide preliminary evidence that integrating physical experiments with virtual simulations enhances students' ability to self-assess their understanding, particularly in complex control engineering topics. Further studies with a larger sample size and controlled conditions could, though, help refine our approach and validate these observations.

We incidentally cite here a few sentences that students wrote in the open parts of the questionnaires, and that be interpreted as suggestions for who implements such a lab:

- *"The physical lab could have gone much more in-depth, for example by writing the code from scratch ourselves, more like a project assignment"*
- *"The virtual lab was probably more instructive, but the practical lab was definitely the most fun!"*
- *"We would have liked to have the lab earlier in the semester so that we could actually allocate time for it"*

5. A DISCUSSION ON THE RELEVANCE OF OUR FINDINGS

Our small test confirms that there are advantages and limitations to using hardware to support specific ILOs and aid self-efficacy. We feel confident that the maglev lab we have been using benefits from several advantages, including its low cost (approximately EUR 85), portability, and open-source design, making it accessible for widespread educational use and making it, we believe, an important tool for the democratization of education. However, we also identified some limitations, such as sensor noise and the need for improved teaching materials to ensure optimal learning outcomes. Addressing these limitations will be key to further improving the lab's effectiveness.

What we are most interested in, though, is insight into student preferences and how these tools may be optimized to aid learning. We cannot state that our study provided definitive insight into student preferences regarding virtual and physical lab experiences, since our dataset suffers from potential selection bias and, in any case, from a limited sample size. But summarizing:

- Of the few students we had, virtually all of them appreciated the hands-on nature of the physical lab, emphasizing its role in reinforcing theoretical concepts with tangible experiences;
- All of them also recognized virtual labs as useful for understanding theoretical foundations before experimentation, but they were less engaging compared to physical setups.
- The combination of virtual and physical labs was seen as highly beneficial (several students expressed interest in more structured transitions between the two).

6. ENVISIONED FUTURE DIRECTIONS

We believe that, as a community, we should create a dynamic cross-university network of educators dedicated to fostering the development, dissemination, and maintenance of low-cost modular take-home hardware platforms for hands-on decentralized learning. This collaborative community, which we informally call "The Microlabs Initiative", will allow educators to co-develop and share innovative educational resources and ideas. Furthermore, we envision these educators to act as "microlab agents", serving as information brokers that connect other teachers with relevant expertise, resources, and opportunities, thus unifying the currently scattered efforts to develop hardware and software setups for at-home or remote learning.

In fact, we perceive a lack of initiatives to pool knowledge and coordinate efforts, offer mentorship, share best practices, and guide educators in integrating hands-on learning modules into curricula. We thus advocate for establishing mentorship networks that support both teachers and learners, promote ongoing innovation & collaboration, and encourage knowledge sharing.

7. CONCLUSION

This paper presents the development and educational contributions that we foresee may be associated with a specific open-source, low-cost, take-home magnetic levitation hardware kit that was initially designed to support students who need distance learning for medical reasons. The kit, along with its self-paced learning materials, has evolved into a versatile tool for teaching control engineering topics across various academic levels. Its success highlights the potential of such setups to mitigate lab space constraints and foster lifelong learning, supporting career transitions into automation-driven industries.

We also envision it as a seed for a broader Microlabs Initiative, which would pool developers of adaptable, open-source resources and expand access to quality control engineering education. Making hands-on learning more accessible aligns with several national competence goals related to sustainability, technological development, and equitable access to education. This approach enables students, professionals, and lifelong learners to engage with key concepts in control and automation, thus contributing to the advancement of the field.

In conclusion, this work presents a series of results we obtained while trying to develop some ILOs in MSc program learners. However, the main message is an invitation for further collaboration to refine and expand the impact of microlabs in general. We encourage educational institutions, industry partners, and researchers to collaborate on improving these learning tools and ensure that hands-on, practical learning remains a core component of control engineering education.

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