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**Conference Paper** · November 2022

DOI: 10.1109/WEEF-GEDC54384.2022.9996233

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Cite as: Kruger, K & Wolff, K, 2022. "Enabling epistemic transitions by integrating virtual and physical laboratory experiences". Proceedings of 2022 IEEE IFEES World Engineering Education Forum - Global Engineering Deans Council (WEEF-GEDC), p 160-165. November 2022, Cape Town, South Africa.

# Enabling epistemic transitions by integrating virtual and physical laboratory experiences

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***Abstract*— As engineering students return to their faculties after the pandemic-induced disruption of conventional teaching, there are new opportunities – and a renewed impetus – to get maximum value out of expensive, yet essential, laboratory practicals (LPs). This paper considers the opportunities associated with the integration of virtual practicals (VPs), which were developed as critical supplements during the pandemic, and the traditional LPs typically part of engineering modules. Reflecting on an implementation in an engineering undergraduate control systems module, and through the lens of Legitimation Code Theory, the paper presents the proposed integration as enabling key epistemic transitions - encouraging conceptual and contextual navigation of different forms of knowledge. Drawing from student and lecturer feedback, the paper concludes that the integrated approach shows promise for effective teaching and learning in the post-pandemic era, but that it requires critical consideration and careful planning in the design and presentation of such initiatives, and continuous monitoring of student progress and understanding, to be successful.**

***Keywords*— *Hybrid learning; control systems; laboratory practicals; virtual practicals; Legitimation Code Theory***

## I. INTRODUCTION

There is increasing pressure on engineering educators to enable students to develop holistic 4th Industrial Revolution (4IR) skills. These are skills required to engage productively in complex problem-solving situations, which include a broad range of stakeholders, dynamically evolving technologies and a triple bottom line ethic: the solution must benefit people, planet and profit [1]. In order to navigate such real-world problem-solving situations, students need to be systematically stretched into more open-ended problem-solving thinking [2]. Industry complaints abound around graduate inability to cope with complexity [3][4], and particularly lament the lack of Science, Technology, Engineering and Mathematics (STEM) technical skills required to tackle Sustainable Development Goals [5].

Engineering Education is concerned with enabling students to build on a foundation of the natural and mathematical sciences as they move into a range of engineering sciences, coupled with tools, technologies and techniques, which are intended to provide solutions for society. As such, training has always sought to bridge theory and practice through the use of available technical resources such as engineering workshops and laboratories. However, as student numbers in tertiary education continue to increase, and technical resources become more sophisticated and expensive, engineering educators are required to be innovative in enabling practical learning that is both viable and successful in enabling students to apply their knowledge in practice. Practicals in fields such as automation are particularly challenging, given not only the expense of appropriate hardware and software, but their rapidly evolving nature. Engineering educators world over have increasingly begun to integrate more affordable simulated or virtual systems to enable students to develop practical skills related to automation and control [6].

The initial hard lockdowns during the COVID-19 pandemic had a significant impact on engineering student practical learning, as entire cohorts could not access laboratories or practical equipment necessary to apply their theoretical learning. Emergency Remote Teaching (ERT) [7] accelerated the need for and development of materials and platforms for remote/online teaching and learning in all aspects of engineering curricula – even for aspects related to the exposure to and engagement with practical problems and applications. A particular challenge for educators was to develop ways in which students could be immersed in real-world type learning opportunities to connect their theory to practice. As engineering students began to return to their faculties in 2022, educators have been in a unique position to consolidate opportunities presented during ERT with new opportunities – and a renewed impetus – to get maximum value out of expensive, yet essential, laboratory practicals (LPs) and the remote/online variants offered during ERT.

Given the reality of massification in tertiary education and the affordances of effective remote/online learning technologies, this paper considers the opportunities associated with the integration of virtual practicals (VPs) – developed as critical supplements during ERT – and the traditional LPs typically part of engineering modules. An "Introduction to feedback control" module, offered at third-year level to mechanical and mechatronic students, is presented as a case study. The paper motivates the value of the proposed integration through the lens of Legitimation Code Theory and the epistemic plane (based on the work of Maton [8], as modified by Wolff [9]). The integration of VPs and LPs supports a strategy to enable epistemic code shifting and stretching, which is deemed a critical step towards a holistic learning experience and developing more effective problem solvers.

## II. THEORETICAL & METHODOLOGICAL FRAMING IN CONTEXT

The engineering faculty at a research-intensive institution in South Africa is engaged in funded programme renewal initiatives. Under the Recommended Engineering Education Practices (REEP) banner [10], a number of case studies have explicitly addressed bridging theory and practice from a theoretically informed perspective, most notably through the use of a Legitimation Code Theory (LCT) heuristic called the Semantic Wave [8]: the explicit, iterative and cumulative movement between abstract concepts and concrete contexts [10]. Two key drivers in this context are resource efficiency and supporting scaffolded, deeper learning. Several REEP initiatives see the effective use of affordable and accessible tools or technologies to scaffold student learning, such as the inclusion of pumps and pipes in a competitive group exercise for a fluid mechanics course [11] or stretching student perspectives into real world appreciation of the mining industry through site visits [12].

The focus of this paper is a third year mechanical and mechatronic engineering course on feedback control, typically offered to a class of more than 200 students. Lecturer observations indicate that students struggle with relating control theory to practical application. Control theory relies on mathematical representations and manipulations to support and simplify analysis, but this mathematical abstraction often poses a barrier to the understanding of the mechanisms and implications of realising control in practice. A consequence of this barrier is that even when students pass the module well, they are often not confident in how to implement their learnings in the real world control challenges that they may face in further studies or industry. A strategic approach to teaching and learning is thus required to aid students in overcoming the complexity of the theory and supporting their understanding of the practical application.

The theory informing professional education contexts is essentially the building of increasingly complex concepts over time and, simultaneously, applying these concepts to practical contexts. Shay et al [13] describe this increasing complexity in engineering as 'epistemic transitions' from the natural and mathematical sciences into engineering sciences, which then shift into application, design and management practices using appropriate technologies. At each stage of the epistemic chain there are artefacts that mediate learning, such as texts, tools and stakeholders. Learning across these epistemic transitions, therefore, is accomplished through adopting the Vygotskian [14] concept of mediated constructivist learning. It is important to differentiate between 'knowledge building' from scratch, as it were, (which is often how constructivism is interpreted) and building understanding by recognising different forms of knowledge at different levels of complexity. Selecting appropriate artefacts to support learning at different epistemic stages is key in professional education.

Legitimation Code Theory offers a set of analytical instruments through which to interpret knowledge practices. The epistemic plane differentiates between concepts and approaches. Simply put, the epistemic plane helps us to see the differences between accepted/ambiguous concepts and fixed/open-ended approaches. In this paper, we use descriptors such as Principles, Procedures, Possibilities and People & Places to identify the different epistemic modes of thinking [9]. Principles are about accepted phenomena and their associated fixed approaches; Procedures are less about a specific phenomenon or concept, but rather focus on fixed methods that could apply to a number of concepts; Possibilities are more open-ended approaches depending on the situation, but where the phenomenon or concept is accepted or specifically determined. The fourth quadrant is People & Places, where there is not a fixed concept or approach; rather, a number of concepts and approaches must be considered. We know from professional problem-solving literature drawing on this plane [9] that effective problem solvers move between fixed and open-ended approaches to concepts ranging from accepted (or standardised) to ambiguous. In other words, they need to think differently at different stages of tackling a particular problem. Supporting cumulative learning [8] means designing opportunities for students to shift between these different epistemic codes or ways of thinking using different mediating artefacts.

Using the epistemic plane, we describe the design and implementation of an initiative to teach engineering students about control using holistically integrated virtual and physical laboratory experiences.

## III. IMPLEMENTATION

This section presents a case study of the integration of a VP and LP within an undergraduate control systems module. The rationale behind the integration of the initiatives, the content of the two initiatives and the nature of the integration are discussed.

### *A. Rationale*

The introduction to feedback control module traditionally comprised a theoretical and LP component. With LPs not possible during the pandemic, a VP that replicates the LP setup was developed in an attempt to maintain the practical component of the module [15]. The two initiatives each have advantages and disadvantages. The LP offers exposure to a real world application, but also introduces complexity such as understanding the workings of equipment, discovering limitations to the theory, and the introduction of external effects. The VP, on the other hand, has low specialised equipment cost, is highly accessible, and presents a more controlled environment. However, it lacks the tangible experience of real world applications.

Considering the above-mentioned characteristics, the two initiatives were integrated to offer a scaffolded learning experience. The VP serves as a precursor for the LP, where the theoretical analysis of the problem can be applied in a simplified, simulated environment. Students can then engage with the LP with a better understanding of the problem and appreciation for the implications of real world control applications. To support the intended holistic and integrated learning experience, it is imperative that the integration of two practical initiatives is designed to support the scaffolded linking of theory and practice, and guides the students through the transitions between the abstract and concrete phenomena.

### *B. Description of initiatives*

The initiatives have a two-fold objective: to provide an immersive learning experience that supports students' understanding of control theory, while simultaneously offering exposure to the real world application of the control theory introduced in the module. Specifically, the presented initiatives focus on the position control of a brushless DC motor using Proportional-Integral-Derivative (PID) and compensator based control strategies.

The two control strategies have different requirements that must be supported by the initiatives. PID control implementation is often based on intuition, trial-and-error and experimentation. Compensator controllers require a more analytical approach for describing the system and designing the controller. It is thus important that the initiatives facilitate both the experimental and analytical approaches.

Both initiatives focus on the position control of a DC motor that rotates a steel disc, as shown in Figure 1. The DC motor is powered by means of an H-bridge motor driver and is equipped with a magnetic encoder to provide feedback of the motor's rotation. The system is controlled by a Programmable Logic Controller (PLC), which generates a pulse-width modulated control signal to drive the motor and reads the motor encoder's output through digital inputs.

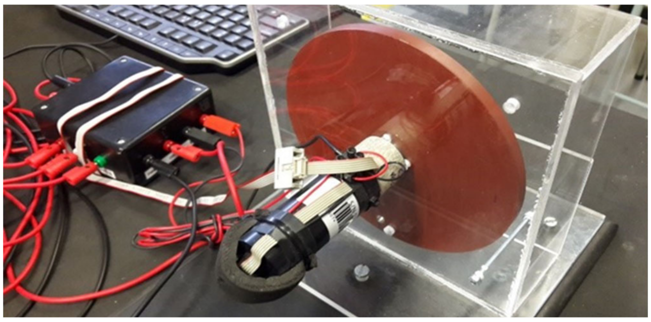

*Figure 1: DC motor system used in the LP.*

The LP was traditionally completed in three phases: system identification (modelling), PID controller implementation and lead compensator controller implementation. Students are guided through the LP by an instruction document for each practical phase and supporting videos, which give background on the system and offer guidance for the setup of practical equipment.

The VP replicates the LP. The VP was developed in MATLAB, using the Simscape library to implement the modelling and visualisation of the motor system and the Simulink library to implement the control of the motor. The Simulink block diagram and the visualisation of the motor's response are shown in Figure 2 and Figure 3, respectively.

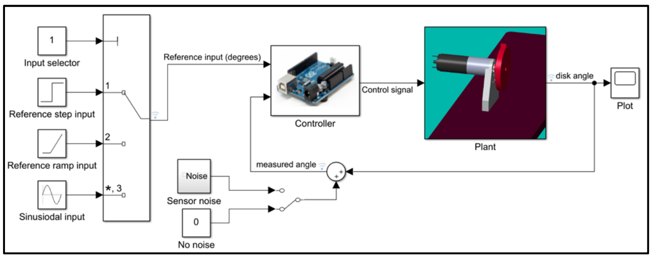

*Figure 2: Simulink block diagram for the VP.*

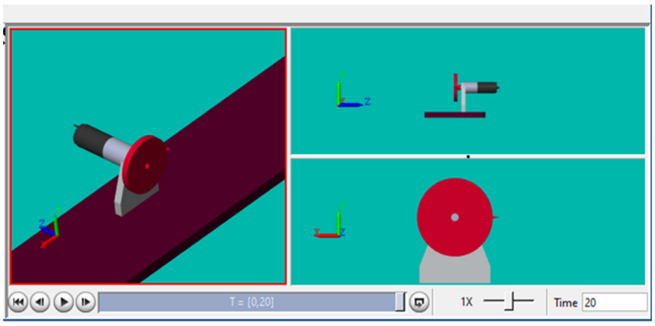

*Figure 3: VP visualisation of the motor's response.*

### C. *Integration of virtual and laboratory practicals*

As mentioned, the aim of integrating the initiatives is to support a scaffolded, holistic learning experience. As such, the discussion of the integration is supported by a visualisation of the integrated initiative's activities on an interpretation of the epistemic plane (as described in section II).

The epistemic plane, which considers the two dimensions of phenomena (ranging from accepted to ambiguous) and procedure (ranging from standardised to open-ended), is visualised in Figure 4, with the four quadrants representing the intended learning objectives: Principles as "Understanding principles"; Procedures as "Applying procedures"; Possibilities as "Identifying opportunities"; and People & Places as "Considering context".

A complexity dimension is added to the visualisation, such that the complexity of a learning activity is indicated by the distance it is located from the origin of the plane (i.e. the further from the origin, the more complex the activity).

The integrated initiative entailed nine activities, which start with VP engagement and progress to LP engagement. The nine activities, which are mapped to the quadrants of the epistemic plane in Figure 4, are summarised as follows:

1. **Students are presented with a real world control problem**. The integrated initiative commences with the introduction of a real world control problem, as detailed in a brief document and supported by pictures and videos of real world examples. The problem is selected to be both familiar and interesting to the students (e.g. a position controller for a camera tracking system or a position controller for a fireboat water cannon).

2. **Students identify the opportunities for implementing feedback control to solve the problem.** The brief further details the requirements that must be satisfied by the developed controller and highlights the theoretical content which the students will have to draw from. Students must thus consider what they have learned from the theory and how that can be applied to the problem.

3. **Students derive a mathematical model representing the physical system.** To support the analysis involved in theoretically designing the control system for the application, a mathematical model of the physical system is derived using well-established modelling principles. However, the derivation entails some simplifications at this stage.

4. **Students design and implement a control system in the VP**. A controller is designed according to theoretical procedures and then implemented in Simulink.

5. **Students visualise and analyse the response of the system in the VP.** The implemented controller is tested in MATLAB (using the Simulink and Simscape tools). The students observe the animated system response and plots of various signals, and tune their controllers to obtain a response that satisfies the application requirements.

6. **Students identify the shortcomings of the VP according to the implications for practical implementation.** At this stage, the students are asked to consider the limitations of the virtual environment, such as the assumption of an ideal actuator and the absence of sensor noise, and the implications thereof for the real world application.

7. **Students perform the system identification in the LP to obtain an accurate mathematical model.** The response of the physical system is captured in experiments and compared to the simulated response of the mathematical model. The parameters of the mathematical model are then adjusted so that the model's response matches that of the real system.

8. **Students redesign and implement the control system in the LP.** Using the tuned mathematical model for analysis, the controller is redesigned and implemented by writing the control code for the PLC digital controller.

9. **Students relate the system's response observed in the LP to the real world context.** At this stage, students must identify the assumptions and limitations of the LP considering the real world application.

Considering the complexity dimension added to the epistemic plane and the plotted learning activities in Figure 4, the scaffolded approach to the integrated initiative is visualised. The intention is to increase the level of complexity with each activity, which results in the spiral mapping of the activities in the epistemic plane. Furthermore, Figure 4 also shows how the initiative transitions between the quadrants of the plane – indicating the different perspectives by which students engage with the problem and the intention to facilitate a holistic learning experience.

The mapping of the activities in Figure 4 provides insight into the characteristics of the two initiatives. The activities related to the VP are mapped closer to the origin, which represents lower levels of complexity. The complexity in the VP is reduced by the controlled simulation environment and the mechanisms to hide complexity from students (e.g. an entire network of function blocks in Simulink can be masked to appear as a single block). In contrast, the activities related to the LP are located further from the origin – representing the complexity of the real world through the presence of external factors (e.g. sensor noise) and the use of equipment (e.g. interfacing with a PLC).

The limitations of the two initiatives, when presented individually, are thus also evident. The VP is limited to simulation and thus in the complexity that can be achieved. The LP represents an initial complexity barrier for students to overcome in order to effectively engage. As such, the integration of the initiatives can be supplementary and thus result in the scaffolded, holistic learning experience that is desired - a 'spiral pedagogy' [16].

## IV. DISCUSSION

The discussion of the integrated initiative is supported by a consideration of both student and lecturer feedback, and an analysis of the initiative towards refinement and adoption.

### *A. Student feedback*

The integrated initiative was presented as part of the Control Systems module in 2021. The students provided feedback on their experience of the initiative by means of a set of yes/no questions and a field for general text input. Table 1 shows seven yes/no questions and the response from the group of 208 students who provided feedback. An analysis of the feedback – both from the set of questions and the general feedback – provides the following insights:

- Both the VP and LP increased the interest and understanding of the students and the initiatives are considered to be valuable to their learning experience.
- The integration of the VP and LP is considered effective.
- The software used has a significant impact on the effectiveness of the learning activity. While students found the MATLAB tools easy to use (though not without initial facilitator guidance), the majority encountered issues with the software at some point that were not directly related to the VP (e.g. installation, configuration, etc.).
- Students did not always see the "big picture" – i.e. the integration of the two initiatives and the flow of the learning activities, and their relation to the theory.

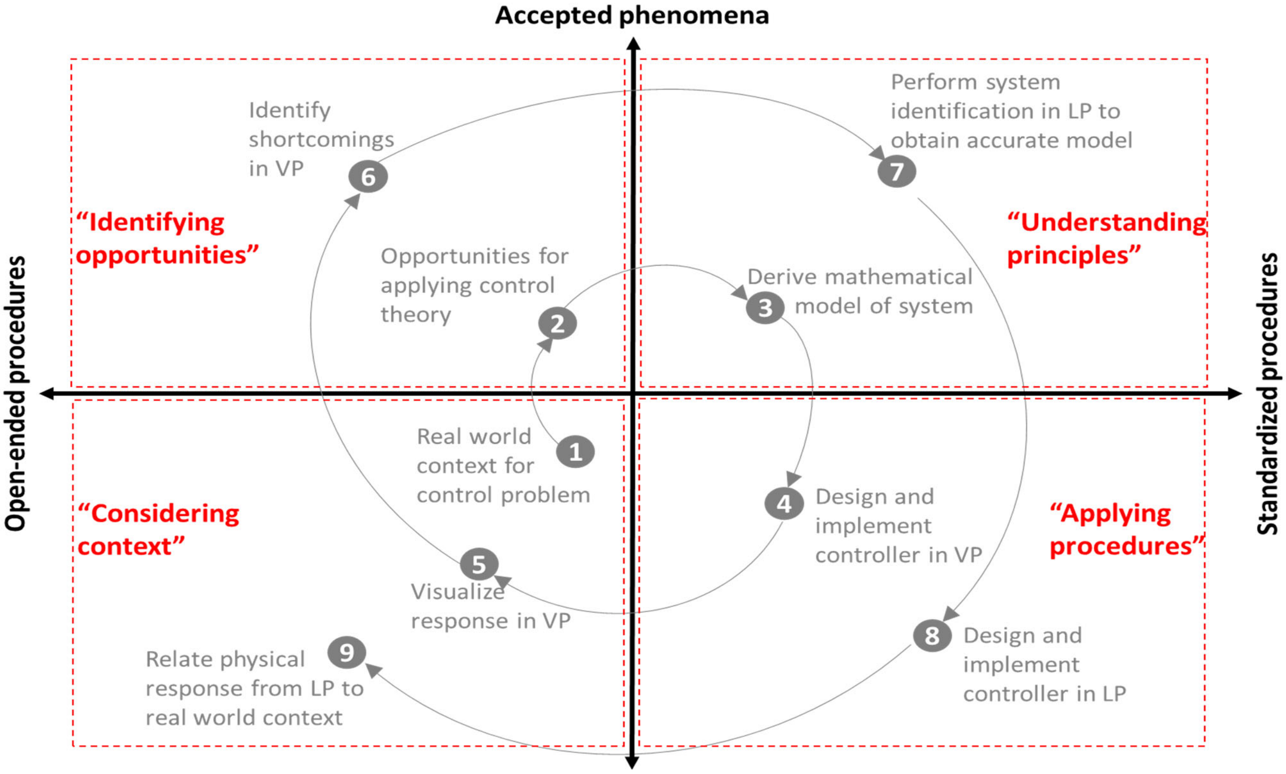

*Figure 4: Epistemic plane mapping of VP and LP integration.*

- Students indicated that time constraints often hindered their engagement, which left them feeling that they could not make the most of the learning opportunities.

### B. *Lecturer feedback*

The lecturer feedback can be summarised as follows:

- It was evident that the students were interested and challenged by the initiative, which led to better understanding of the practical application of control systems in general.
- To enable students to effectively engage with the integrated initiative, very clear communication and guidance is required throughout. The brief and assignment/instruction documents must be clear and concise, must facilitate the transitions between learning activities and between the VP and LP, and must continuously link the practical initiatives to the theory.
- The design and integration of the initiatives requires notable thought, planning and time.
- The presentation of the initiative requires communication and engagement with the students and learning assistants at every step.

### C. *Analysis*

The analysis of the student feedback showed that the integrated initiative was mostly successful in its objective of providing a scaffolded, holistic learning experience. However, there are issues concerning the use of software and the continuous interaction with and support of students throughout the initiative that require refinement. The lecturer feedback confirms that the initiative achieved the objective, but highlighted the challenges of presenting the initiative in terms of the time and attention that is required.

From the feedback, it is evident that the integration of the VP and LP initiatives has merit. While some aspects require refinement, the value of scaffolding complexity and the different perspectives of engagement as facilitated by the integrated initiative is notable.

Further work will focus on the refinement of the initiative and the design of new initiatives of this kind for other topics in the module. The educational perspective, such as the use of Legitimation Code Theory and visualisation of the epistemic plane, will be further explored.

## V. CONCLUSION

The paper discusses the opportunities for the integration of VPs and LPs to support epistemic transitions. The paper draws from Legitimation Code Theory and uses the epistemic plane to visualise the integrated practical initiatives from an educational perspective. The integrated initiative consisted of nine sequential learning activities, which transition between the quadrants of the epistemic plane and at incremental levels of complexity. The impact of the integrated initiative is discussed in terms of lecturer and student feedback. The paper concludes that the integrated approach shows promise for effective teaching and learning in the post-pandemic era, but that it requires critical consideration and careful planning in the design and presentation of such initiatives, and continuous monitoring of student progress and understanding, to be successful.

*Table 1: Student feedback.*

| **Question** | **YES** | **NO** |
|---|---|---|
| 1. The LP made the module more interesting. | 96% | 4% |
| 2. The test procedures of the LP improved my understanding of control theory and application. | 86% | 14% |
| 3. Being able to interact with the virtual system in the VP made the module more interesting. | 76% | 24% |
| 4. Being able to view the animated response of the VP was very valuable. | 78% | 22% |
| 5. The VP supports the LP by giving more exposure to practical control application. | 79% | 21% |
| 6. With the VP, I encountered serious issues with MATLAB. | 65% | 35% |
| 7. The MATLAB (Simulink) tools are easy to use and improve my interest and understanding. | 77% | 23% |

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