Student Feedback on Educational Innovation in Control Engineering: Active Learning in Practice

Amélie Chevalier, Kevin Dekemele, Jasper Juchem and Mia Loccufier

***Abstract*—Contribution: An education innovation in control engineering using practical setups and its evaluation based on a three-year student feedback study and examination grades. Background: Based on extensive research, education's transition towards active learning and more practical experience has been shown to increase learning outcomes. Contrary to virtual and remote labs, a practical session with an individual setup for each student provides the most practical experience. Intended Outcomes: To show a positive effect on learning performance by integrating practical sessions in basic control engineering. Application Design: Presenting low cost setups which can be mass produced and adapt to the course's growing complexity. These setups are evaluated during a three-year feedback study. Findings: The developed setups increased understanding of theoretical concepts. The new methodology significantly improved students' average grades. The students' interest in control theory is triggered. This case study could guide other institutions towards successfully implementing highly individual practical sessions for large groups.**

***Index Terms*—Student Assessment, Active learning, Educational Setting, Experiential learning, RLC setup, Air levitation setup, Control Engineering**

I. INTRODUCTION

CONTROL engineering is nowadays a multidisciplinary subject. It has applications in chemical engineering [1], electro-mechanical engineering [2], electrical engineering [3], applied physics [4] and computer science [5]. Hence, basic control courses arise which have to address a broad range of engineering students. Also, reference works on basic control engineering provide often multidisciplinary examples to relate to a large variety in backgrounds [6].

A basic control engineering course deals with subjects such as time-domain controller design, feedback control, frequency-domain controller design, PID control, etc. The number of undergraduate students attending these courses increases [7]. The students find the topics taught in basic control courses challenging and difficult to understand due to their abstract nature. Research has shown an improved student performance and a better understanding of abstract concepts when active learning techniques such as practical sessions are applied [8]. However, the combination of limited financial resources and the booming number of students, provides a challenge for the organization of lab sessions.

Research has been done on how to provide practical sessions to large groups of undergraduate students. A trade-off decides which type of active learning technique is applied: *financial cost* vs *individual practical experience*.

Virtual laboratories have the advantage that no real setup is required, i.e. low financial cost [9], [10]. A simulator allows students to perform measurements on simulated systems often via internet. This provides a possible downside to this type of active learning: the lectures depend on the quality of internet connection which is not always stable when many users log in simultaneously. Also, as the lab is provided virtually, the practical experience is limited.

Remote labs also use internet to provide lab sessions to large number of students [11]. The advantage of remote labs is that only one setup is needed and students log on remotely. The downside again is the dependency on the internet connection. Compared to virtual labs, a remote lab provides more practical experience as the students study a real process.

Practical sessions where students perform individual measurements on a real setup present the benefit of hands-on experience [12], [13]. The main downside is the large number of setups needed to provide this learning experience, i.e. high financial cost [13]. To reduce the number of needed setups, lecturers might choose to give multiple sessions where the total group of students is divided into smaller groups. However, this requires an increased amount of time of the teaching staff which is not always possible.

Based on the performed literature study, a trade-off between the required number of setups and the student's individual experience has to be kept in mind when choosing an appropriate method of active learning. Therefore, the authors state a need for low-cost set-ups where students can still have the important benefit of hands-on experience. In the authors opinion, this practical experience is of utmost importance to gain insight into the abstract topics taught in a basic control course.

At Ghent University, the basic control course is taught to a multidisciplinary group of students. The goal in this research is to find an optimal trade-off where students can have individual hands-on experience during class sessions which can still be time-efficiently organized. Therefore, two low-cost, portable lab setups were developed which can be mass produced to allow practical sessions for large groups on location: an RLC setup [14] and an air levitation setup [15], [16] presented in Section II. Student feedback over multiple academic years has been done to analyze the performance of the setups on the learning outcomes which is given in Section III. Section IV discusses the results followed by the conclusion.

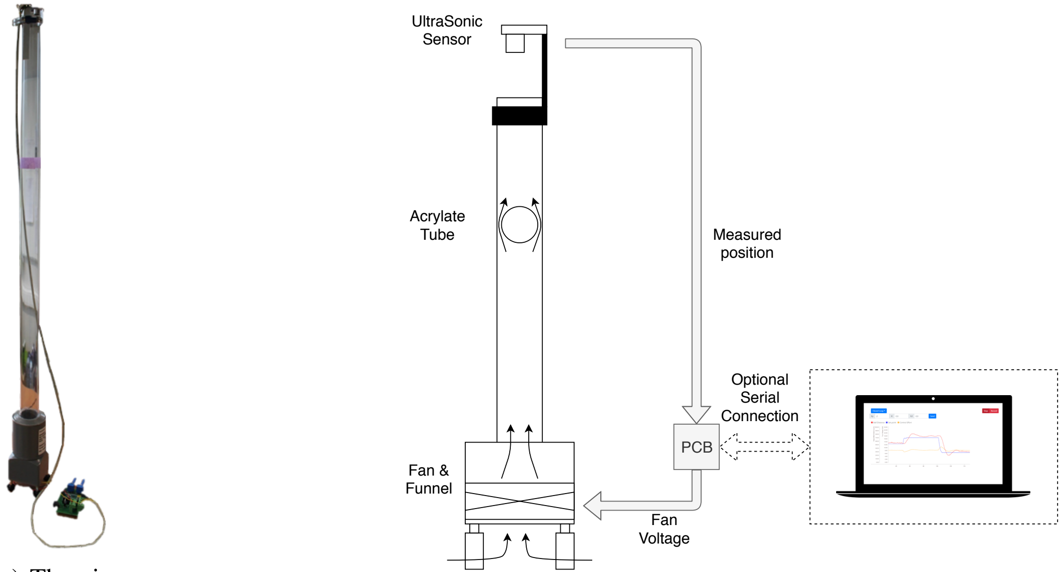
II. MATERIALS AND METHODS

In this section, a short description of the used setups is provided. A details discussion on the development of the RLC

All authors are with the Department of Electromechanical, Systems and Metals Engineering, Ghent University, Belgium

a) The RLC setup in a portable container.

b) The breadboard with the closed-loop PI-controller. The control loop is indicated with the important signals.



c) The air levitation setup.

d) The schematic representation of the air levitation setup.

Fig. 1: The educational setups.

setup can be found in [14] while the air levitation setup is similar to systems found in literature [15], [16]. Both setups are presented in Fig. 1.

A. *RLC setup*

The RLC setup allows the student to mimic a wide variety of dynamical systems by selecting suitable electrical components, thus appealing to a multidisciplinary group. The RLC setup is fully battery powered, making it movable and workable on any location. Thus, it even poses a solution to lectures from home during 'lock down' situations and distance learning. It consists of a plastic box (see Fig. 1a) with dimensions $23 \times 15.5 \times 6$ cm which contains a breadboard, a pushbutton (NO), two 9V batteries, one 1.2V battery, a NI USB-6000 data acquisition card, various resistors, capacitors and inductors and two in-house designed Printed Circuit Boards (PCBs): a differentiator and an analog PI controller (see Fig 1b). In total 90 setups were realized to provide active learning opportunities to large groups of students.

The RLC setup in open-loop configuration provides the students with insight into system dynamics. The pushbutton connects the 1.2 V battery with the process in an instance allowing the students to investigate process step responses of first-, second- and higher-order systems.

Closed-loop dynamics and concepts such as negative feedback with PI control can be investigated by closing the loop (see Fig. 1b). Negative feedback is achieved using a differentiator PCB and a PI controller PCB [14]. Students can tune the controller by selecting the correct resistance value (for P-action) and capacitance value (for I-action).

Interaction between the setup and the personal computer of the student can be done using any hardware that is able to sample a voltage signal. In this case, the National Instruments USB-6000 is chosen. This deliberate choice introduces a professional DAQ-card to the students. Open-source software Python 3.x programming language is used because i) it is well-documented and free, ii) a python library *nidaqmx* for National Instruments for data-acquisition exists, and iii) Python 3.x is taught in the undergraduate basic programming course. This allows the student to maintain a knowledge continuation. Moreover, the signal processing/analysis is done in Python as well using the *Python Control Systems* library. A GUI is created that can be used to change the sampling time, to start and stop the acquisition, and to save the data array to a .csv file. The code for the GUI is available in a GitHub repository and can be easily downloaded by the students.

B. Air levitation setup

The air levitation setup (Fig. 1c) is a nonlinear system with an unstable equilibrium. Feedback control is required to stabilize the ping-pong ball allowing the teacher to convince the students of the capabilities of control theory. The setup consists of a fan introducing an airflow into a 1 m long clear acrylate tube with a inner diameter of 50 mm. This allows the user to position a ball inside the tube. The choice is made to use a PVC-U square-to-round down-pipe adapter to funnel the air, allowing for production of 70 setups. The HC-SR04 ultra-sonic sensor has been chosen due to a good accuracy-cost trade-off and still introducing the concept of measurement noise. To read the sensor values and control the system, the Arduino Nano is chosen in combination with an in-house designed PCB featuring terminals for the fan, sensor connectors, a push-button and two potentiometers serving as input for the Arduino (Fig. 1d).

A program on the Arduino Nano allows the students to manually control the voltage to the fan and thus the position of the ball. The students can test their own control skills compared to the designed controllers. It also allows the students to investigate the open-loop dynamics and perform parameter tuning tests such as the oscillation technique to tune the PID parameters based on the work on Ziegler-Nichols [6].

The controller for this setup a digital controller, contrary to the fully analogue control in the RLC setup.

A serial communication can be made to visualize and record the measurements with a graphical user interface (GUI) dashboard made in JavaScript. In this GUI, the user can change the program state from manual control to closed-loop feedback control. During feedback control, the PID values can be adjusted dynamically.

III. EDUCATIONAL VALUE

This section presents the educational value of the developed setups in a basic control course. It discusses how the setups are used, the students' feedback and the effect on the learning performance.

A. Application in Lectures

The basic control course at Ghent University is taught to 180 students. The course theory is given in 12 contact sessions which are interlaced with 12 exercise sessions. Before the educational innovation, these exercise sessions were on paper. Now, three of these sessions are replaced by the setups: Class 1: Experimental modeling, Class 2 : Closed-loop control and Class 3: Computer aided design. Beforehand, materials for self-study are being provided for both setups. This maximizes the teaching time dedicated to control engineering concepts such as system dynamics and feedback control.

Combining both setups, brings the students in contact with:

- both analog control (RLC setup) and digital control (air levitation setup)
- an industrially used data acquisition card (RLC setup)
- systems with significant measurement noise (air levitation setup)

Innovation is done over the course of two academic years. The first year only the RLC setup was implemented (3 classes). The second academic year the air levitation setup was also introduced resulting in 2 classes using the RLC and 1 class with the air levitation setup.

1) Year 1:

The students were split into two groups of 90 students allowing one setup per student.

Class 1: The students have to perform open-loop measurements on an RC circuit, a circuit with 4RC combinations in series and an RLC circuit. The students become familiar with first-, second- and higher-order stepresponses.

Class 2: The students have to use Ziegler-Nichols tuning rules, to design P- and PI-controllers for a fourth order system with 4RC combinations in series. The process reaction curve is approximated by a first-order-plus-dead-time model. The measured response of the P-controller on the fourth order system is shown in Fig. 2. The students are asked to read the final value, the rise time, the overshoot and steady state error, familiarizing them with these concepts. Comparing the P- with the PI-controller, allows the students to grasp the concept of integrating action, i.e. the steady state error disappears.

Class 3: The students have to perform computer aided design (CAD) in both time and frequency domain. Using Python code, the root-locus techniques are used to design a P- and PI-controller. The second part of the task deals with the use of Bode and Nyquist plots in Python to design the controllers and assess concepts such as robustness and stability. Based on the obtained root-locus plot of the open-loop system, the closed-loop characteristics can be changed based on specifications such as damping, overshoot, settling time, etc. Afterwards, the stability criteria of Bode and Nyquist can be used to asses the stability of the designed closed-loop process. Concepts such as robustness, phase margin and gain margin are addressed in this class.

2) Year 2:

During the second academic year, the air levitation setup is also introduced in Class 3. For this class the group is split into three groups of 60 students. Each student assembled their setup and used the GUI on their own laptop to interact with the setup.

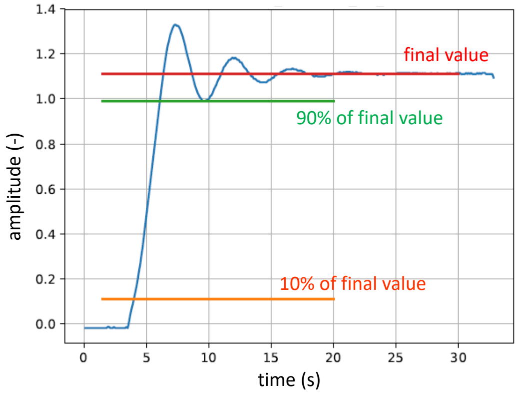
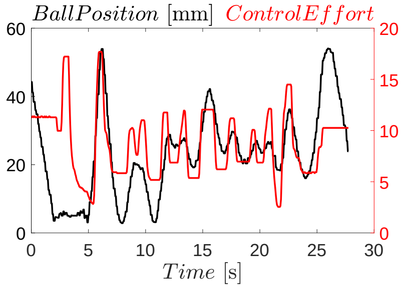
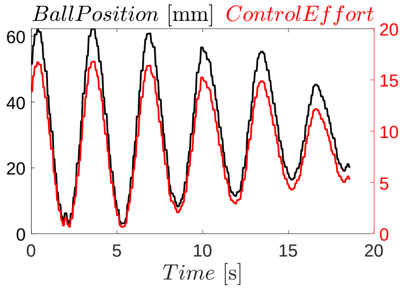


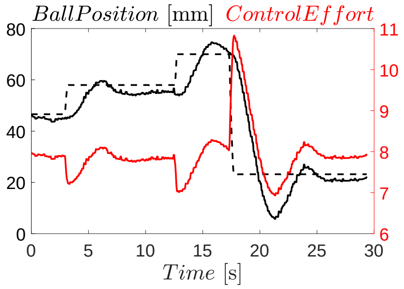
Fig. 2: Step response of the fourth-order system with P-control.



(a) Manual control



(b) Oscillation



(c) P-control. Dashed line is the setpoint.

Fig. 3: Lab assignment measurements.

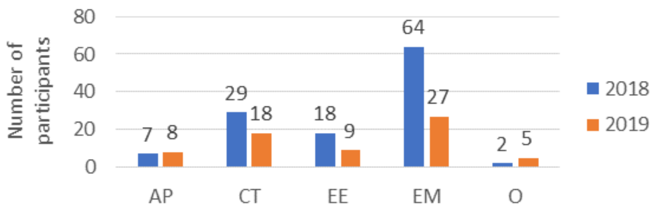


Fig. 4: Number of survey participants for each specialization.

TABLE I: The survey.

Topic	Question	2018	2019
Use of laptop	Q1A: Were the guidelines of the faculty concerning required laptop specifications clearly communicated?	✓	✓
	Q2B: Do you have the required knowledge to independently install the needed software?	✓	✓
	Q1C: Is the current infrastructure satisfactory to have efficient laptop practicals?	✓	
	Q1D: Did you have enough guidance in case of computer/software problems?		✓
RLC Setups	Q2A: Are the setups an added value to better understand the theoretical concepts	✓	✓
	Q2B: Is there need of extra information about breadboards?	✓	✓
	Q2C: Are the developed PCBs userfriendly?	✓	✓
	Q2D: Is the provided information for each practical session sufficient?	✓	✓
Air levitation Setups	Q3A: Are the setups an added value to better understand the theoretical concepts		✓
	Q3B: Is it an added value to see how a controller is programmed in the microcontroller?		✓
	Q3C: Should there be a GUI shows multiple signals and allows you to change the control parameters without re-uploading the Arduino code each time?		✓

Class 3: First, the user has to try to stabilize the ball manually by manipulating the fan voltage. On Fig. 3a, a user attempted to position the ball at 30 cm. Because of the unstable nature of the process, the user has great difficulty doing so.

Second, autotuning is done using the Ziegler–Nichols oscillation method [6]. The program state is changed to closed-loop feedback control, either by pressing the pushbutton or by changing the state in the GUI. By increasing the K_p of the P-controller, a constant oscillatory behavior of the ball position can be obtained (see Fig. 3b). Corresponding K_p, K_i and K_d can be calculated using the tuning rules of Ziegler-Nichols.

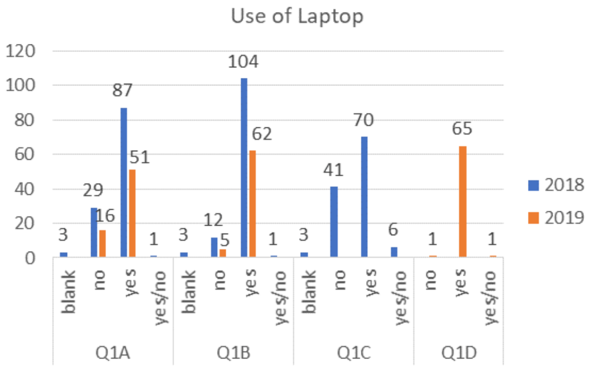
After designing the controller, the user can apply either a P-, PI- or PID-controller. On Fig. 3c, a P-controller was used. As opposed to the manual control, the closed-loop PID controller is now able to stabilize to the setpoint, given a small static error. By applying a PI-controller the static error vanishes. The GUI allows the user to easily discover the influence of increasing/decreasing the K_p, K_i and K_d.

B. Student Feedback

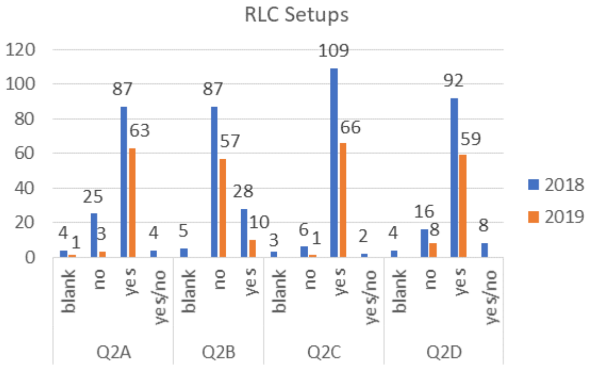
At the end of each academic year, a feedback survey was presented to the multidisciplinary group of students to evaluate the setups. Different specializations are present in the student group: applied physics (AP), chemical technology and material science (CT), electromechanical engineering (EM), electrical engineering (EE) and others (O). A set of closed-ended YES/NO questions are asked in combination with open-ended commentary boxes where the students can formulate their comments. This allows both quantitative and qualitative analysis of the feedback results. The first academic year, the survey only polled the RLC setup. The second academic year, both setups were polled.

The first year, the survey was given to the students on paper at the end of the last practical session. The second year, the survey was given to the students via an online platform. This difference reflected in the number of participating students (see Fig. 4). The online survey has been taken by only 37% (67/180) of the students while the paper survey reaches 66% (120/180) of the students.

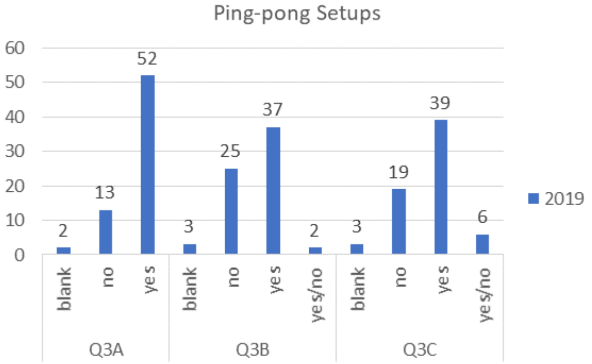
The survey questions are given in Table I together with an indication whether or not they were included in the survey from the specific year. The results of the survey are presented in Fig. 5a, 5b and 5c for each topic. Note here that a number of students left the YES/NO questions blank or even encircled both answers and motivated via the commentary box.



(a) Use of Laptop



(b) RLC Setups



(c) Air levitation Setups

Fig. 5: Results of the survey.

C. Results

To evaluate the learning performance, the examination results (marks out of 20) are investigated. Three years are included in this research: year 0 (2017) is the year before the education innovation project, year 1 (2018) is the year where only the RLC setups are used and year 2 (2019) is the year where both setups are combined. The percentage of students in each score interval is shown in Fig. 6.

Statistical analysis is performed to check the effect of the setups using 1-tailed t-tests with significance value 0.05. Comparing the exam results from 2017 with those of 2018, yields a p-value of 3.7E-6. This indicates a significant difference in the exam results when introducing the setups. To test the effect of the intermediate actions, the results of 2018 and 2019 are compared, yielding a p-value of 3.4E-5. This shows again the significant difference in exam results between both years.

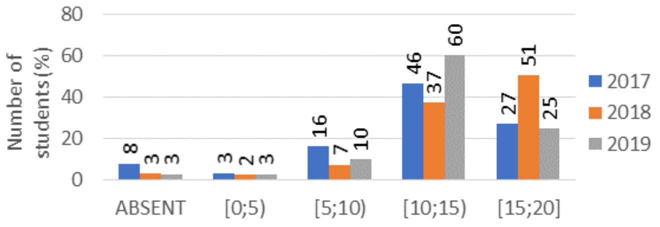


Fig. 6: Student results for the examination.

IV. DISCUSSION

This section presents a discussion on the education innovation project based on student feedback and examination results. It is organized according to the topic in the survey and indicates whether action has been taken in the intermediate phase of the innovation project, i.e. in between year 1 and 2.

1) General: After implementing the RLC setups in year 1 (2018), the first set of feedback results have already been examined. A total of 120 students provided valid survey responses in 2018. The second survey in 2019 yields 67 valid responses.

2) Use of laptop:

Q1A: 72,5% in 2018 and 76,1% in 2019 indicates that the faculty laptop requirements are well communicated.

Q1B: 86,6% in 2018 and 92,5% in 2019 of the students can install the required software independently.

Q1C: The answers indicate a divided group opinion. The infrastructure of a classical auditorium (used in 2018) is insufficient for the practical sessions. Dead laptop batteries have to be taken into account .

Action: Based on the feedback, the practical sessions in 2019 are moved to an open-plan student foyer where each table has electrical power.

Q1D: 97,0% indicate a good level of guidance in case of computer/software problems.

3) RLC setups:

Q2A: 72,5% in 2018 indicate that the practical setups are an added value to better understand the theoretical concepts. However, when investigating the specialization of the students who do not see the added value, a distinction becomes clear. The total of 25 'no' answers to question Q2A are divided as follows: 6 AP, 5 CT, 3 EE and 11 EM. This shows that from the students in applied physics 85,7% does not see the added value of the setups. Contrarily, only 17,2% in chemical technology, 16,6% in electrical engineering and 17,1% in electromechanical engineering agrees with that statement.

Action: The goals of the practical sessions were explained in 2019 in more detail and a second setup was introduced to appeal to a wider group of students.

*Result:*In 2019, 94,0% of the students indicate an added value of the practical setups which is a clear increase and shows a positive effect of the intermediate action.

Q2B: 72,5% in 2018 indicate there is no need for. However, due to the mixture in specialization, part of the student group is missing this background.
Action: For the practical session in 2019, extra information has been made available on the use of breadboards.
Result: A decrease in students in need of extra information is visible from 23,3% in 2018 to 14,9% in 2019. This indicates that the intermediate action of providing extra information on breadboards, had a positive effect.

Q2C: 90,8% in 2018 like the user-friendliness of the PCBs. The open sections of the survey in 2018, indicate some students having problems with component failure.
Action: The component failure issue has been addressed.
Result: An increase to 98,5% is observed in 2019 with respect to user-friendliness.

Q2D: 76,6% in 2018 and 88,0% in 2019 indicate that the provided materials are sufficient.

4) Air levitation setups:

Q3A: 77,6% indicate an added value of the setup.

Q3B: The answers indicate a divided group opinion. 55,2% learned from the Arduino code, however 37,3% is not interested in the microcontroller programming. These findings correspond with the students' specialization.

Q3C: 58,2% indicate that a GUI to plot the measured signals and adapt the control parameters would be appreciated.
Action: The GUI presented in Section II-B has been developed.

5) Examination Results: The results in Fig. 6 show a clear decrease in number of absent students when using the setups indicating an increased confidence. The percentage of passed students (10/20 or more) increases from 73% in 2017 to 88% and 85% in 2018 and 2019 respectively.

From the statistical analysis and the exam results, the conclusion can be drawn that the introduction of the lab setups in 2018 has a positive effect on the learning outcome. The changes in 2019, yield a significant difference on the examination outcomes. Important here is the increased focus on the use of python, which was still basic in 2018, and CAD controller design. This increases the difficulty of the course slightly which is observed as a shift in the examination results from the [15;20] interval to the [10;15] interval.

V. CONCLUSION

This work presented a three-year student feedback study on the introduction of practical setups for control education. The introduced setups are presented and how they are implemented in the educational context of the basic control course is addressed. A set of closed-ended questions with multiple-choice answers are used for student feedback in combination with open-ended commentary boxes. The results of the student feedback indicate a positive effect on the examination results after introduction of the setups. An increased student confidence and a clear added value of the setups on the insight of theoretical concepts in control engineering is observed.

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Amélie Chevalier obtained her PhD in Engineering at Ghent University in 2019 while being teaching assistant. Her post-doc research is focused on system control with a main focus on control of knee biomechanics.

Kevin Dekemele is pursuing a PhD in Electromechanical Engineering since 2015 at Ghent university in combination with being teaching assistant. His main research topic is nonlinear vibration control of mechanical structures.

Jasper Juchem is pursuing a PhD at Ghent University on the topic control of underactuated mechanical systems. He is also a teaching assistant for Control and Structural Dynamics courses.

Mia Loccufier is professor at Ghent University teaching in mechanical vibrations, structural dynamics, systems dynamics and modeling and control. Her research is focused on the dynamics and control of technical systems with main research themes: passive vibration control; stability and bifurcation analysis of nonlinear systems; control of underactuated mechanical and biomechanical systems.