

# Facilitating learning progress in a first control course via Matlab apps<sup>★</sup>

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**Abstract:** It is well-known that students learn substantially more if a lecture is complemented by active inquiry-based activities and problem solving than from only passively listening to a lecture. Naturally, this requires the teacher to include elements into the course such as laboratories, group projects, tutorials and interactive e-learning modules. For the most effective teaching concept, all such components of the course work are tightly intertwined and work together towards the same goal and learning objectives. Therefore, **we show in this paper how Matlab apps can be included into the wider effort of learning facilitation in an introductory automatic control course.** Among other advantages, Matlab apps can offer an unlimited number of exercises and examples that can be generated automatically, they offer interactive interfaces that can include gamification aspects such as levels and highscore lists to increase the motivation, and they can be done at the students' own pace. The course evaluation and the feedback from students at the University of Stuttgart suggest that the inclusion of the Matlab apps presented in this paper is indeed a success.

*Keywords:* E-learning in control engineering, control education, educational games.

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## 1. INTRODUCTION

It is long known that (inter-)active exercises improve the learning progress of students (e.g. Dale (1969); Knight and Wood (2017)). As summarized by Carmean and Haefner (2002), active exercises generally emphasize involvement in real-world tasks, are intertwined in judgment and exploration, use active learning techniques as well as emphasize practice and reinforcement. Being consistent with the mindset of student-centered teaching with the goal to facilitate learning, every teacher should hence explore how active elements can be integrated to complement and improve the classical (lecturing) formats. However, any methods and active elements are only effective if they cater a targeted goal and address specified learning objectives well aligned with all other components of the course.

One possible way to include active exercises into a course work is to add e-learning components (Bencomo (2004)). Compared to other active elements such as tutorials and laboratories, digital modules like e-learning games have the additional advantage that they increase the self-determination of students as they grant flexibility in time and place of learning. Furthermore, e-learning games have the advantages that they can offer an unlimited number of exercises and examples through random generation, they can increase the motivation by introducing levels and highscore lists and they can be done at the pace of the students. Therefore, e-learning can be a very effective supplement to a course which includes lectures, labora-

tories, tutorials, etc. and **it has already been successfully integrated in numerous lectures via computer-aided controller design through visualization (Piguet et al. (1999); Guzmán et al. (2006); Díaz et al. (2019)), interactive tools linked to remote laboratories (Salzmann et al. (2019)) and eLearning games as in Schweickhardt et al. (2006); Münz et al. (2010); Ramírez-Ramírez et al. (2013); Ke (2016), amongst others.** This paper provides an example of how a typical introductory lecture on automatic control can be supported by some small goal-oriented e-learning applications. More specifically, in this context of blended learning, we present **a framework of MATLAB apps for students to engage in exercises linked to the basic learning objectives of a first control course to improve factual, conceptual and procedural knowledge with respect to specific topics.**

The paper is organized as follows. We first briefly introduce the course *Introduction to Automatic Control* that is held at the University of Stuttgart and present our conception of teaching. Based on this conception, we derive student-centered learning objectives, which form the basis of the development of the MATLAB apps that are tailored to facilitate learning for students and target some specific learning objectives. We then describe the four MATLAB apps that we developed by explaining their goals, functionality and didactical concepts. Finally, we present our experience with these MATLAB apps together with the student evaluations of the past two years. Since the course *Introduction to Automatic Control* at the University of Stuttgart has a typical format and content for a first course in automatic control, we hope that our experience as well as the MATLAB apps themselves are transferable to other courses and help other lecturers. All apps are made available under the CC-BY NC ND license and can be found on our homepage [www.ist.uni-stuttgart.de/teaching/elearning/matlab-apps/](http://www.ist.uni-stuttgart.de/teaching/elearning/matlab-apps/).

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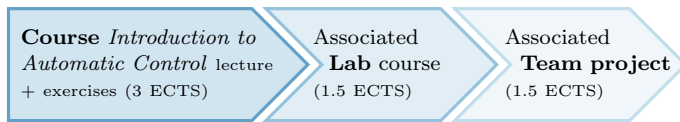


Fig. 1. The course *Introduction to Automatic Control* is followed by an associated lab course and team project in the following semester. The lab course and the team project are based on the content of the course *Introduction to Automatic Control* as well as require some first experience with MATLAB.

## 2. AUTOMATIC CONTROL COURSE AT THE UNIVERSITY OF STUTTGART

The set of MATLAB apps presented in this paper accompanies the course *Introduction to Automatic Control at the University of Stuttgart*. This course is part of the curriculum of different engineering study programs at the University of Stuttgart. Most of the approximately 100-150 students, which is a common size for a basic engineering course in Germany, are third year undergraduate students. The course corresponds to 3 ECTS (European Credit Transfer System) and consists of 21 hours of lectures, i.e. 90 minutes of lecture per week over a period of 14 weeks. The students are additionally offered 21 hours of exercises, where they can work on common control problems and solution strategies with help from instructed tutors.

Generally speaking, this course covers the basics of analysis and control of linear time-invariant (LTI) systems in the frequency and time domain. This includes the Nyquist stability criterion, controller design via loopshaping, state-space representation, pole placement, controllability and observability. While in the lecture the theoretical concepts are introduced and toy examples are presented and offered as exercises, more application-oriented tasks await the students in the following semester via the associated lab course and the team project as illustrated in Fig. 1, where the more involved control problems have to be solved in a less and less instructed fashion.

The students in the course *Introduction to Automatic Control* have, to a large extent, a common basis in mathematics and system dynamics, but otherwise different study programs. The course *Introduction to Automatic Control* is for some students the starting point of their specialization in control theory and for other students it may be their only contact with automatic control altogether. It is therefore critical to teach the most basic concepts and understanding for those students for which it is the only control course, as well as build a solid foundation and motivate those students that plan to specialize in this field.

### 2.1 Conception of teaching

In Kember (1997), results of different studies about the conceptions of teaching at universities and their implications are summarized and reviewed. According to this survey, changing the teachers' perspective from a content-oriented conception focused on content transmission towards a student-centered and learning-oriented conception focused on learning facilitation is the very basis to improve teaching quality and learning outcomes. Fully subscribing

to this belief, we are consistently committed to employ more interactive and student-centered teaching methods. While the lecture is still of major importance within the module *Introduction to Automatic Control*, we consider it one element in a wider effort to facilitate learning.

### 2.2 Teaching agenda through learning objectives

There is no general answer to the question which tools and methods are the most effective ones, this heavily depends on the formulated goals. For teaching a course, all teachers hence must first ask themselves what the learning objectives of the course are. With the results from Kember (1997), learning objectives should be student-centered as our mindset is not to cover a certain topic but for the student to learn certain ideas and skills. Learning objectives should also break down the task into small steps and the specific cognitive processes. Furthermore, using action verbs within the learning objectives communicates the expectation and intellectual effort required. In this regard, we make use of Bloom's taxonomy of cognitive learning objectives as described in Adams (2015). Finally, learning objectives should be measurable in that they point to a clear assessment that can easily be checked. On the basis of carefully chosen learning objectives, the module can be planned aligned with these objectives: from content to methods to examination (even further to what they would need for advanced courses or in industry). The interested reader in this direction of "constructive alignment" is referred to Biggs (1996) and references therein.

Carefully chosen learning objectives hence set both teaching and assessment agendas. Therefore, we carefully collect all learning objectives of the module *Introduction to Automatic Control* and make them available to the students categorized into basic and advanced objectives. Furthermore, according to Biggs (1996), "the teaching methods we choose need to engage students in activities that are likely to require them to perform in the way nominated in the [learning] objectives". Evaluating our learning objectives carefully led to a variety of teaching and learning methods, where e-learning apps are one very valuable approach within a wider effort.

### 2.3 Application of MATLAB apps

In the conception of teaching as presented in Sec. 2.1, we find that e-learning and especially MATLAB apps offer a great opportunity, as an additional element in a variety of efforts to facilitate learning, to engage students in activities connected to our learning objectives. With respect to this goal, MATLAB apps provide the following advantages:

- Especially for learning objectives categorized into 'basic objectives' defining the minimum knowledge expected from students after a first control course (e.g. in the revised Bloom's taxonomy: *remember, understand, apply*), MATLAB apps can offer unlimited exercises and examples through random generation of, for example, different transfer functions.
- Through interactive interfaces, students are required to actively engage with the tasks. Being actively engaged with the material has shown to improve

learning progress within students significantly (Dale (1969); Knight and Wood (2017)).

- The MATLAB apps automatically make students familiar with MATLAB and hence implicitly prepare them also for the Laboratory and the Project Work, which follow the lecture (cf. Fig. 1).
- Including application examples, different levels and competitions, e-learning games can enhance the ambition and eagerness of students. This can motivate students not only to use the apps extensively, but also to become more motivated in the course.
- Employing MATLAB apps has the additional advantage of increasing the self-determination of students as well as the flexibility in time and place of learning. Students can progress at their individual pace.

There are also alternatives to using MATLAB. One might lose some students for whom the effort of installing MATLAB (available for free for students at the University of Stuttgart) is an inhibitor. On the other hand, for most students, the MATLAB apps nudge them into installing and working with MATLAB early on. While the look and feel in MATLAB apps is restricted and the design might seem old-fashioned to some of the students, an advantage is that the initial implementation and maintenance effort for the chosen tasks is manageable by interested and motivated students. Therefore, small MATLAB apps are easily created and can be tailored to the needs that appear. The teacher can thereby react on typical shortcomings or put emphasis, contrary to using off-the-shelf solutions such as Díaz et al. (2019); Quanser (2019). Altogether, for the specified tasks and goals as described before, the developed and presented MATLAB apps are suitable. To have a broader view on different possibilities for eLearning modules generally, the reader is referred to Díaz et al. (2019), and for other complementing approaches within the course *Introduction to Automatic Control* to Pauli et al. (2020).

Within Section 2, we introduced our student-centered conception of teaching, which led us to clearly defined learning objectives. Some of these learning objectives can be very well supported by e-learning games. More specifically, we established above that especially for basic learning objectives, MATLAB apps constitute a precisely targeted tool with different advantages. In the following section, we move from theory to practice and present the specific goals of the four developed apps and how they target specified learning objectives within the course *Introduction to Automatic Control*.

### 3. MATLAB APPS

In the following, we present the four developed apps in more detail. The language of the app is automatically set to English if the language of MATLAB is not German. Further explanations and background information can be found in the respective apps. Please note that the full range of features in the apps can only be appreciated by actually testing the apps.

#### 3.1 Nyquist Criterion App

**Goal** The goal of this app is that the students can apply the Nyquist criterion to determine whether the closed loop

is stable from the frequency response and location of the poles of the open loop.

**Description** The Nyquist Criterion App randomly generates suitable transfer functions of the open-loop plant  $G_0$ . The left plot in the app then visualizes the Nyquist plot of the open loop from  $\omega = 0$  to  $\omega = \infty$ . If necessary, the right plot shows the detail view near the critical point  $(-1, 0)$ . Furthermore, the number of poles in the open right half plane (denoted  $m_0$ ) and the number of poles on the imaginary axis (denoted  $a_0$ ) are also given. The students' task is to determine  $\Delta\Phi(G_0(j\omega))$ , which denotes the encirclements  $\Phi$  (in degrees) of the Nyquist plot of the open-loop  $G_0$  around the critical point  $(-1, 0)$  from  $\omega = 0$  to  $\omega = \infty$ , and whether the closed loop is stable or not with the Nyquist criterion. The interactive interface of the Nyquist Criterion App is shown in Fig. 2.

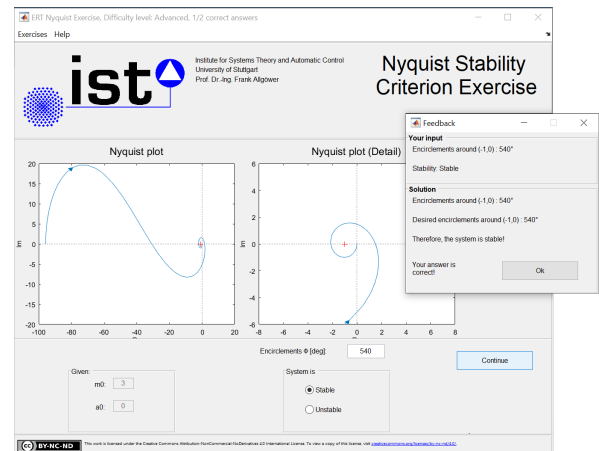


Fig. 2. Screenshot of the Nyquist Criterion App in the level "Advanced" with feedback dialogue.

**Didactical concept** The students receive direct feedback after submitting their answer. The feedback consists of their answer and the correct answer such that they can directly recognize a possible mistake. Furthermore, there are three difficulty levels within the Nyquist Criterion App. While the first level creates rather easy examples of the open-loop transfer function, the medium and advanced level offer more involved transfer functions. Students with more than 80% correct answers as well as a total of at least ten correct answers within the easy and medium level are automatically transferred to the next level together with a pop-up congratulating the student. Within the advanced level, students that have a quota of correct answers of 90% together with at least a total of 20 correct answers receive a similar pop-up attesting their Nyquist criterion skills. This generates a gaming element, usually triggering students to become ambitious and eager to finish the game. If a student masters all levels then the learning objective as stated above is fulfilled.

#### 3.2 Stability and Robustness App

**Goal** The goal of this app is that the students can identify robustness margins (i.e. phase and gain margin) of a closed loop given the Bode or Nyquist plot of the open-loop system. Furthermore, the students shall be able to decide on the basis of a Bode or Nyquist plot of an open loop

whether the closed loop can be stabilized by a proportional controller  $K(s) = k_p$ ,  $k_p \in \mathbb{R}$  and if so, identify the largest interval  $k_p \in (\underline{k}_p, \bar{k}_p)$  for which the closed loop is stable.

*Description* In the Stability and Robustness App, either a Nyquist plot visualizing the locus of the open loop from  $\omega = 0$  to  $\omega = \infty$  or a Bode plot of the randomly generated open loop is shown. In the difficulty level "Easy", the students are supposed to determine the robustness margins of the closed loop from the open loop, as exemplarily shown in Fig. 3. In the difficulty levels "Medium" and

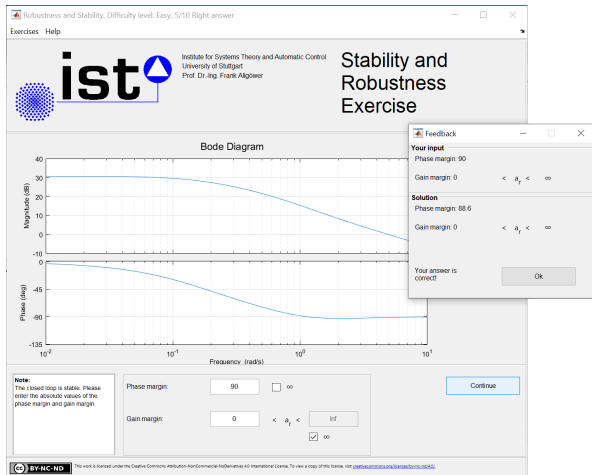


Fig. 3. A screenshot of the Stability and Robustness App in the level "Easy" where the robustness margins have to be determined.

"Advanced", the students must decide whether the closed loop can be stabilized by a proportional controller  $K(s) = k_p$ ,  $k_p \in \mathbb{R}$  and if so, they have to identify the largest interval  $k_p \in (\underline{k}_p, \bar{k}_p)$  for which the closed loop is stable.

*Didactical concept* The students receive direct feedback after submitting their answer. Analogously to the Nyquist Criterion App, there are three difficulty levels and the students are automatically moved to the next level with a congratulations pop-up after proving their knowledge through correct answers. If a student masters all levels then the learning objectives as stated above are fulfilled.

### 3.3 Loopshaping App

*Goal* The goal of this app is that the students can apply loopshaping to a given plant such that the closed loop satisfies certain control objectives. This includes that students know the effect that a proportional, integral and lead controller have on the Bode diagrams of the open loop and how the controller performance in closed loop can be identified from the open-loop Bode diagram. Finally, they should be able to manipulate controller parameters to reach specific performance criteria of the closed loop.

*Description* The Loopshaping App is a significantly more extensive tool than the other three apps. This is also due to the fact that our learning objectives for this app are more involved and require a break down into several different steps. Furthermore, before this app was introduced, students especially had difficulties picturing, grasping and applying the steps involved in the loopshaping approach. The Loopshaping App consists of four major parts:

- (1) A tutorial about loopshaping including introductory tasks. Here, the students are iterated through designing P-/PI-/PD-/PID-controllers<sup>1</sup> to achieve certain control criteria for a rather simple underlying system.
- (2) A loopshaping competition with a highscore list, where the students can apply what they have learned to develop a controller for a CD player by either using a PID controller or designing a transfer function.
- (3) Design of a customized task. The students can enter the required transfer function and specify the desired parameters themselves and select which controllers shall be used. The app then generates a task from the given transfer function to be solved by the student.
- (4) Infinitely many random control tasks. In this mode, the app generates random control tasks such that the students have the opportunity to practice loopshaping with an unlimited number of systems.

To solve any of the four tasks above, a Bode diagram is shown wherein one can choose which transfer function is plotted (i.e. the system to be controlled, the current and previous controller, the current and previous open loop consisting of plant and controller). Furthermore, one can additionally choose to plot the amplitude of the sensitivity and the complementary sensitivity or the Nyquist diagram of the open loop. In a table "Controller Goals" next to the Bode plot, the currently achieved and desired values for relevant control properties are stated:

- The steady-state error should disappear.
- The crossover frequency of the system has to hold (within a specified accuracy).
- The phase and the gain margin of the overall system must be greater than the margins defined here.

The students can set the relevant parameters of the controller via active input fields. Furthermore, the currently active controller is displayed as an equation. Moreover, there is also the advanced mode, which deactivates the display of the closed-loop characteristics: control error, crossover frequency, phase margin and gain margin. Fig. 4 shows the competition within the Loopshaping App (with a posteriori cleared solution fields to not withhold the fun of participating in the competition from the reader).

*Didactical concept* The first task is organized in a tutorial style such that the first four subtasks can only be done sequentially and build up on each other. Through additional information in the text field to the right, the basic controller structures from the lecture are revised. Altogether, the game here takes the role of an instructor, monitoring the progress, giving immediate feedback and additional information. Complementing the tutorial style part of the app, the competition is posed more openly and is meant to spark the interest and ambition of students. If certain criteria are fulfilled, students can enter their username into a highscore list, which further engages students in the task and motivates them. Another positive side effect of such competitions is that gamers tend to exchange experience and share strategies to improve their score. Due to the advanced mode and the possibility to pose ones own problems, this app also engages the very good students of the course.

<sup>1</sup> Note that the D-element is realized as a Lead element in the app.



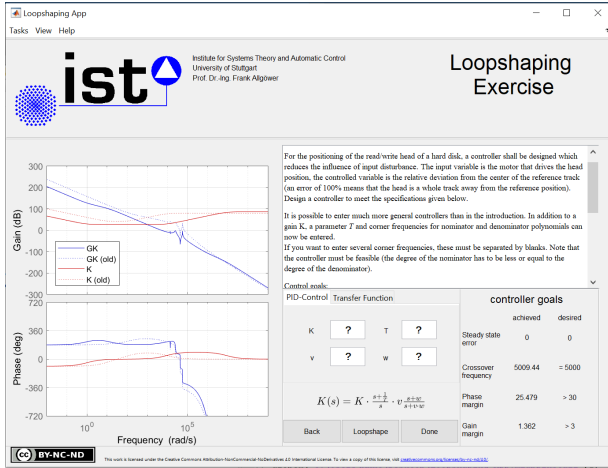


Fig. 4. Screenshot of the Loopshaping App during the loopshaping competition.

### 3.4 State Space App

**Goal** The goal of this app is that the students know how to compute the controllability and observability matrix and can thereby determine whether a system is controllable or observable, respectively. Furthermore, the students should be able to calculate the closed-loop poles with state feedback or the poles of the error dynamics of a given observer. Finally, the students should be able to calculate the state feedback or observer for given desired closed-loop poles and error dynamics, respectively.

**Description** This MATLAB exercise consists again of three different difficulty levels. In the difficulty level "Easy", the controllability or observability matrix is to be determined and used to decide whether the given system is controllable or observable as shown in Fig. 5. At the difficulty level "Medium", a system together with a controller or an observer is specified, and the corresponding poles of the closed loop or the error dynamics of the observer are to be determined. The third level "Advanced" specifies a system and a set of desired poles of the closed loop or the error dynamics, for which the students have to design a suitable controller or observer.

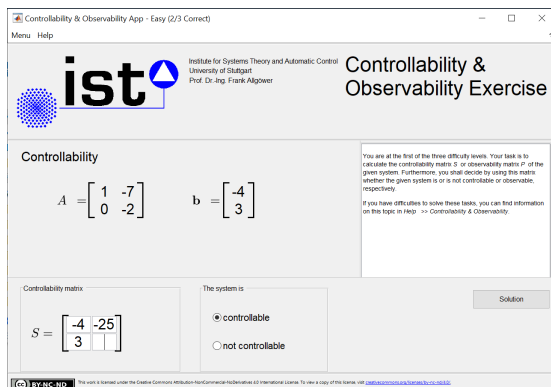


Fig. 5. Screenshot of the State Space App with a controllability exercise in the level "Easy".

**Didactical concept** This app is designed similarly to the Nyquist Criterion App and the Stability and Robustness App, with similar level structure and didactical concepts.

## 4. EXPERIENCE AND RESULTS

### 4.1 Experience of teaching staff

One lesson learned during the last two semesters was that students are significantly more likely to use the e-learning apps if they are introduced and shown during the lecture, or possibly even included interactively in the lecture. Indeed, the Loopshaping App and Nyquist Criterion App are well suited to demonstrate loopshaping or the application of the Nyquist criterion during the lecture. Altogether, the students seemed very engaged with the available e-learning tools and the participation in the loopshaping competition was significant. Furthermore, questions about the basics that are treated within the available MATLAB apps were less asked during office hours and the topics seemed to be better understood also with respect to the measured learning outcomes in the exams.

### 4.2 Student evaluations and feedback

Each semester, we evaluate the course *Introduction to Automatic Control* through an anonymous evaluation system. First, the students indicate to which extent (in the range from one to five) they agree to course related statements. Secondly, they have the option to include additional feedback ("What do you especially like about the course?" and "Which suggestions for improvements do you have?") into a blank field. The evaluation sheets filled out by the students are centrally and automatically evaluated, analyzed and sent back to the lecturer.

The evaluation of the students concerning the e-learning offers accompanying the lecture *Introduction to Automatic Control* was generally very positive. Fig. 6 illustrates the result from the last two years regarding the question to which degree the students agree to the following statement (originally posed in German): "The additional interactive e-learning games (MATLAB, Submarine,..) help to understand and apply the contents of the lecture." In both years, most of the students agree that the additional e-learning

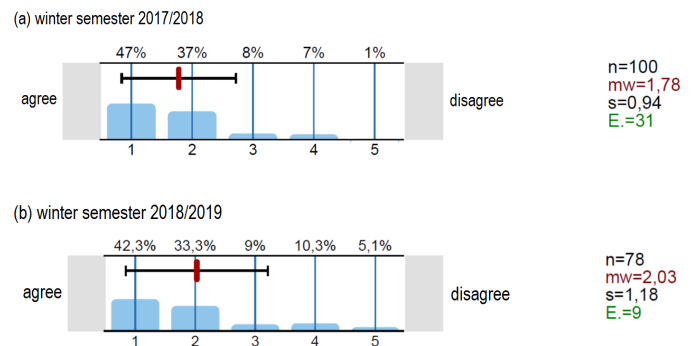


Fig. 6. Histogram of the student agreement with the following statement: "The additional interactive e-learning games (MATLAB, Submarine,..) help to understand and apply the contents of the lecture". The percentage above the histogram denotes the relative frequency of the response, the mean (mw) and standard deviation (s) are also plotted into the histogram. Further information given is the total number of answers (n) and abstentions (E).

games, including the MATLAB apps, help them to understand and apply the contents of the course. Moreover, in the optional free comment field about what the students like especially about the course, the e-learning offers as one tool among a wider effort of different materials seems to be highly appreciated by the students. In the winter semester 2017/2018 (2018/2019), eight (four) students, out of 64 (50) who wrote any comment, emphasized that they appreciate the variety of materials and exercising options in general, eight (eleven) students appreciated the e-learning games among which five (eleven) explicitly praise the MATLAB apps. Examples of their comments include (originally in German): "The MATLAB apps support the learning process very effectively", or "[I like especially the] MATLAB Apps for exercising and improving understanding (e.g. Loopshaping App)". There were also suggestions for improvements of the apps mostly during the semester. It has been a request by students, e.g., to include the design of a customized task in the Loopshaping App, such that they can use this app in subsequent lectures or the lab course. Another important conclusion from the feedback was that if the e-learning games do not run immediately and smoothly, they will be used significantly less.

When comparing vertically, the most comments of the students about what they especially like about the lecture was in both years connected to lecturers (e.g. motivation, humor, explanations, energy). This shows how important the personal contact to the students is and that, in our opinion, interactive apps can only complement but never replace in person interaction. However, for the winter semester 2018/2019 the MATLAB apps were the second most mentioned component of the module that the students especially appreciated and in the winter semester 2017/2018 the multitude of exercise options (i.e. including the apps) was mentioned the second most. This leads us to the conclusion that the MATLAB apps are indeed a successful tool to complement other in person components, as a majority of the students embrace this format of exercising and learning (cf. Fig. 6), and for some of them the tools are even outstanding from the other efforts around this module. Last but not least, the apps have proven to facilitate the learning objectives at which the apps are targeted, as experienced in the office hours and the exams. Altogether, we therefore consider the introduction of the MATLAB apps in this first control course a great success.

## 5. CONCLUSION

Based on a student-centered conception of teaching, we defined learning objectives that are made available to the students. For some of these learning objectives, e-learning games are very well-suited to facilitate the learning progress. In this context, this paper exemplarily presents how a framework of MATLAB apps can accompany and support a first automatic control course targeted at clearly specified learning objectives. Based on the feedback and evaluations of students at the University of Stuttgart, a vast majority of the students used the apps and consider them a help in understanding and applying control concepts. From our experience, the key factors for the success of such MATLAB apps for facilitating learning include (i) transparency of the learning objectives, i.e. clearly categorizing the topics

covered in the apps, (ii) interaction and gamification aspects (e.g. loopshaping competition with highscore), and (iii) introducing and using them in the lecture. We hope that our tools are of value for the community and we highly appreciate any feedback for improvements and extensions.

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