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Teaching Automatic Control for Chemical Engineers

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ABSTRACT

In this paper, we present our recent advances and achievements in automatic control course in the engineering study of cybernetics at the Faculty of Chemical and Food Technology STU in Bratislava. We describe the course elements and procedures used to improve teaching, learning, and administration experience. We discuss on-line learning management system, various teaching aids like e-books with/without solutions to practice examples, computer generated questions, video lectures, choice of computation and simulation tools. The course is provided in the presence form of study for about 20 students, but it relies on on-line tools and methods. Starting from this academic year, flipped design of the course was designed. We describe our experience in the preparation of such a change and some initial feedback from the students. The course concentrates on input/output linear approximation of processes in chemical and food technology and discusses poles/zeros, process dynamics, frequency and time methods, closed-loop system, design and tuning of PID controllers, root-locus analysis. Although the majority of laboratory exercises is performed using simulation tools, we also provide easy-to-use laboratory device that can be given to all students to work either at school or at home.

Keywords: Education, Process Control, MATLAB, Students' Feedback

INTRODUCTION

The rapid advancements in information technologies have affected engineering education, particularly in the fields of chemical engineering and automatic control. This trend was even strengthened during and after the Covid-19 pandemic.

The course on automatic control is a core component in master programs in the field of cybernetics. The students usually define it as a difficult one, due to heavy use of mathematics, physics, and chemical engineering principles. In addition, IT skills (programming and simulation languages) are needed as well. Therefore, it is of utmost importance to try to improve the learning experience of the students and, at the same time, to maintain the depth of the studied topics.

One innovative approach to enhance student engagement and learning outcomes is the flipped classroom model [3,4,8]. In this model, traditional lectures are replaced with online video lectures that students can watch at their own pace outside of class. In-class time is then used for active learning activities, such as problem-solving, discussions, and group work. This approach has been shown to be effective in promoting deeper understanding and critical thinking skills.

This paper shares our experience and shows an overview of the structure and methods used to improve teaching, learning, and administrative tasks for the course on automatic control for master students at the Faculty of Chemical and Food Engineering, STU in Bratislava.

PROGRAM AND COURSE CONTENTS

The course *Theory of Automatic Control I* is taught at the Institute of Information Engineering, Automation, and Mathematics in the first semester of the master study in the program *Automation and Information Engineering in Chemistry and Food Industry* accredited under the field of Cybernetics. The program is thus focused on applications control and IT in process industries. It contains several main branches represented by a series of courses:

- Theory of automatic control: fundamentals, state-space methods, multivariable control, process control, robust control, intelligent control, MPC.

- Modeling: fundamental models, identification, separation processes, data processing, machine learning, process optimization.
- Technical means of automation: sensors, actuators, PLC, DCS, visualization, HMI.
- IT: web programming, databases, object-oriented programming, git, LaTeX.

Students that enroll in the program all come from chemical engineering bachelor programs at the faculty but have different levels of knowledge in cybernetics and automatic control. About 10-20% of them completed the bachelor program Process Control and are advanced, but the rest of them are students mostly with chemistry, biology, food or chemical technology backgrounds and with no previous experience with control. Therefore, the institute organizes mini-courses on MATLAB and Python programming, data treatment, and IT skills at the beginning of the first semester.

The course is planned with 2 hours of lectures and 3 hours of seminars/exercises per week and its contents is as follows:

- Mathematical modeling of continuous-time systems: general principles of modeling, linearization, deviation variables, state-space representation.
- Input-output properties: from states to I/O representation, from transfer function to states.
- Poles, zeros, process dynamics.
- Frequency characteristics: complex numbers, frequency responses.
- Control performance: time, frequency, integral indices, poles and zeros.
- Closed-loop system: structures, components, stability, regulation, tracking problems.
- PID controller: review, types, properties, anti-windup, bumpless transfer.
- Root-locus techniques for analysis and design.
- PID controller tuning.

This is a fairly standard course content for the introductory course in automatic control. As it is taught at the chemical engineering faculty, all students have knowledge and experience with standard engineering mathematics and physics, steady-state material and enthalpy balances, chemical engineering fundamentals.

The processes selected for modelling and control are built on this knowledge and include mainly heat exchangers and water tanks. They are used repeatedly in different course topics. A simple heat exchanger can be represented by a first-order transfer function, and a series of them can be used for linear systems of higher order. Two or more water tanks (without pumps) represent stable nonlinear processes, suitable for linearisation, comparison of linear and nonlinear behaviour. If a pump is included, it results in unstable integrating process that needs to be stabilised using feedback control. We note that specific control of more complicated processes is studied in the third semester in the course Theory of Automatic Control III (advanced process control).

STUDY SYSTEM AND SUPPORT

The course frontend is provided using LMS Moodle that has been in use at the faculty since 2005. Therefore, teachers have a good knowledge of the system. The most used activities/sources are files, links to videos, assignments, and quizzes. Institute courses provide full read access to all teachers - the aim is to know about material and ways how it is provided to students - to increase compatibility level between courses. In addition, limited read access is provided for anonymous course guests (https://elearn.uiam.sk/course/view.php?id=95).

The backend to the course is maintained in Gitlab repository of the institute. This covers LaTeX sources to all study materials, MATLAB and Python sources to scripts. This helps to follow the evolution of the course and facilitates transitions between instructors.

Starting from this school year, flipped design has been used. Since Covid19 times, lectures have been recorded. The most recent 2 hours lecture recordings (approx. 20 hours total) were cut into smaller logical pieces (5-10 minutes each) and uploaded to YouTube. One or two Moodle Lesson activities were then prepared from every lecture and there are one or more questions after each video. Each Lesson begins with definition of its objectives and aims for students. This activity must be completed prior to the actual week. The experience from the first year shows that the average duration of this individual activity takes about 3 hours. Students can repeat the lesson questions, and the best result is used for grading. Knowledge of the material shown in lecture recordings is required in the final oral exam.

As the flipped-design classroom requires students to dedicate significant time to preparing in advance individually, it makes the flipped design a good candidate for putting all students with different backgrounds on the same level. This way, the students get familiar with novel topics at their own pace, and they apply the acquired knowledge in practice at school during active tutorials and seminars.

Instead of the traditional lecture, students come to Active tutorial, supervised by the lecturer. The first part of the Active tutorial reviews the Lesson, student results and their errors in question answers. Then, the lecturer states problems that students try to solve. Students are encouraged to work in groups, discuss together. There are two types of PDF documents available: unsolved problems with blank space to be filled and the same information with complete solutions. Therefore, students can review again the solutions provided by the lecturer. The level of complexity is chosen in such a way that no computer solutions/simulations are needed, a mobile phone or pocket calculator suffices.

The seminars are held in groups of approximately 10 students in computer laboratories, where every student works with their computer. The teaching assistant follows up on the topic from Active tutorial and gives tasks to the students. Some of the tasks are focused on manual derivations and mathematical analysis to improve students' critical and technical thinking. The teaching assistant strongly leads this part. Most of the tasks are focused on programming and simulations performed in MATLAB. During this part, the students are actively engaged, and the teaching assistant provides technical support.

Regarding the grading of the seminar, students obtain 2 assignments during the semester, and they have approximately 2 weeks to work on them at home and to submit a protocol. At the end of the semester, the students take the final test using MATLAB and MATLAB Simulink. The grade from seminars is calculated as the arithmetic mean from the two assignments and the final test.

Study materials of the course consist of selected parts from the monograph [6]. Of course, the material is standard, and any appropriate feedback control book can be used. In addition, an electronic textbook specially tailored to this course is also provided. Each chapter corresponds to one course topic, and it is divided into:

1. Topic goals, overview and summarization of the theory - this is related to the lecture recordings.
2. Examples - this corresponds to problems treated in Active tutorials.
3. Practice examples - this is the topic for the seminars with the teaching assistant.
4. Problems, MATLAB and Python snippets - supplementary information for interested students.

The individual chapters are used during the seminars. In that case, practice examples in the respective Moodle topic do not contain solutions. However, documents available for download within Moodle course also provide the full version with solutions. This helps both students (if they want to review) and if there is a replacement for a teaching assistant.

The overall course grade consists of completion of Lessons (15%), seminars (25%), and oral exam (60%).

ELECTRONIC QUIZZES AND QUESTIONS

Assessment of student knowledge can be realized in Moodle using questions. A collection of questions can form Moodle activity Quiz, or it can be part of the Lesson activity. The Quiz question bank supports various plugins - the standard ones are for example true/false, multichoice, short answer, matching, numerical, calculated, drag-and-drop, matching. The Lesson module can use only a few of them, and, unfortunately, for the time being, it is not possible to have only a single question bank for both Quiz and Lesson.

Among other contributed plugins for the Quiz activity, STACK questions have proven to be very beneficial for our engineering the course. STACK [7] is a powerful open-source assessment system for mathematics and related disciplines, designed to enable students to answer questions with mathematical expressions. STACK uses the Computer Algebra System (CAS) Maxima [5] to evaluate the answers. It can accept equivalent expressions (random order of terms, factorization, etc.), it provides controlled randomization and inspection of deployed variants, multipart questions, customized feedback and response trees.

Figure 1 shows an example of a STACK question on inverse Laplace transform. The student specifies the answer which is immediately evaluated to show how it will be interpreted by the system. Therefore, the student can check the answer for correctness before the actual evaluation. Such questions can greatly improve the learning experience.

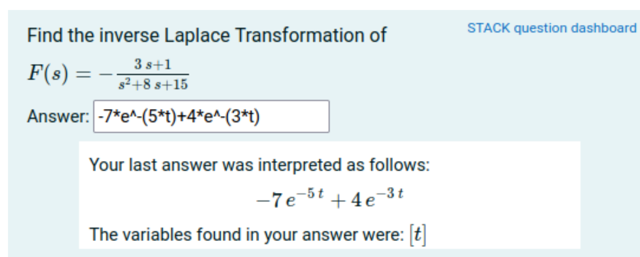

Figure 1. Inverse Laplace transform question using STACK.

Due to current shortcomings of the Lesson module, we generate multiple variants of numerical multichoice or short answer questions outside of Moodle using our solution based on MATLAB and XML [1]. MATLAB (or any other language) can be used as a scripting and templating engine to generate automatically many identical questions with different numerical values. Every question then consists of two input files: template XML file with placeholder for numerical values at appropriate places and computational part that generates suitable random sets and prepares the numerical values. MATLAB scripts then generate a desired type and number of questions and produce an output neutral XML file. Then, XSLT processor is employed to generate a desired output format - this can be for example PDF to be printed (paper quiz with versions for students and for teachers) as well as import XML format suitable for Moodle -- for both Quiz and Lesson activities. One of such random questions is provided to a student using the Cluster and Random question within the page features of the Lesson activity (Figure 2).

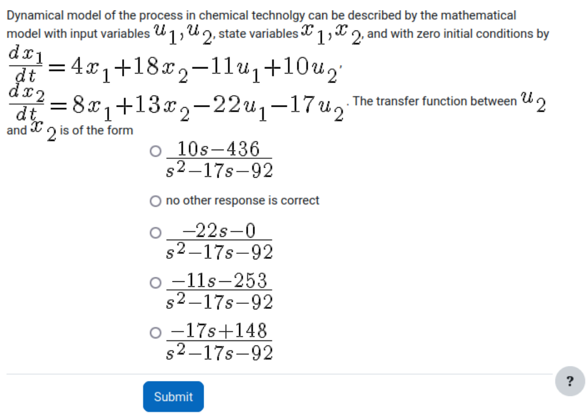

Figure 2. A randomly generated question in Lesson module using MATLAB, XML and XSLT.

REAL-TIME EXPERIMENTS

Figure 3. Flexy2 device.

Although most of the semester work is based on simulations, we also devote some time for real-time experiments. Flexy2 device [2], shown in Figure 3, is used to demonstrate practically some steps in process control: selection of signals, observation of dynamical behavior, model estimation, PID controller design.

Flexy2 is a simple dynamical system with one input and one output. The manipulated variable is air flow from a computer fan that propels an air column in an upward vertical direction. The effect of air flow is measured by a flexible sensor that is deployed in the air column. The output variable is electrical resistance of the flexible sensor based on a degree of bend that is caused by hydrodynamic push of air. Figure 4 shows normalized step responses for steps of different magnitude and direction.

The device has a nonlinear behavior, with some minor oscillations at higher air speed. Its small dimensions make it suitable as a portable device and students can borrow it to work at home. Its API is provided both in MATLAB and Python. Both manual and automatic operations are available, the two tuning knobs at the device are programmable, they can be used for manual control or for tuning of controller parameters.

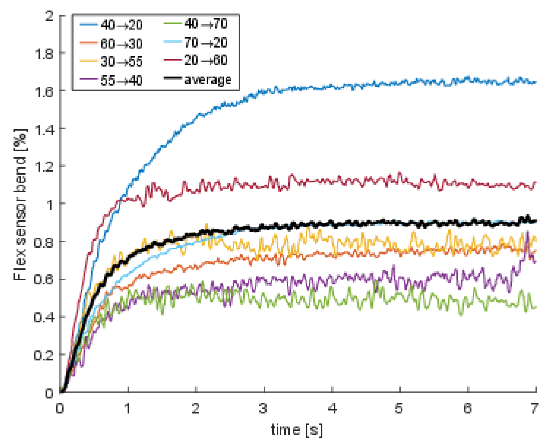

Figure 4. Normalized step responses of Flexy2 device.

Students are expected to measure the step responses of the process, estimate its model, design PID controllers using Ziegler-Nichols and SIMC methods, and observe/quantify control performance. Therefore, these experiments usually take place at the end of the semester when they have covered all these topics theoretically.

FEEDBACK BY STUDENTS

This section provides an overview of the students' feedback collected weekly during the semester, as well as one final survey at the end of the semester.

The main aim of the weekly survey is to examine the students' satisfaction with the subject and teaching process. Feedback is nonmandatory, anonymous, and is collected at the end of every lecture/Active tutorial and seminar. Besides other questions, we ask students to rate the clarity and appropriateness of the presented topic on a scale from 1 (worst) to 5 points (best). In 2023, when the lectures had the standard format, we collected 62 answers during the semester with an average score of 4.76 and a minimum value of 3. One year later, after introducing the Active tutorials, we collected 77 feedbacks with an improved average score of 4.95 and a minimum value of 4.

Students can provide verbal feedback as well, but they usually do not dedicate much time to a deeper evaluation at the end of every lecture or seminar. Therefore, we created one final survey at the end of the semester, focused on the novel form of the automatic control theory course. The feedback was provided from 10 students. The questions are as follows:

1. How do you evaluate the difficulty of the course?
2. How do you evaluate the coverage of the course by study literature?
3. How do you evaluate the novel format of lectures – Active tutorial?
4. How do you evaluate the format of seminars?
5. To what extent do you think it is possible to work on seminars independently without the guidance of a teacher?

First, we asked students about their opinion on the difficulty of the course on a scale from 1 (very easy) to 5 points (very difficult), see Figure 5. 70% of students rated the difficulty with 4 points, and the remaining 30% rated the difficulty with 3 points, which supports our experience that students usually see this course as a difficult one.

We were also curious about students' opinion about the coverage of the course by study literature on a scale from 1 (worst) to 5 points (best), see Figure 6. 50% of students were satisfied with the study materials and rated them with 5 points, and 40% of students rated them with 4 points.

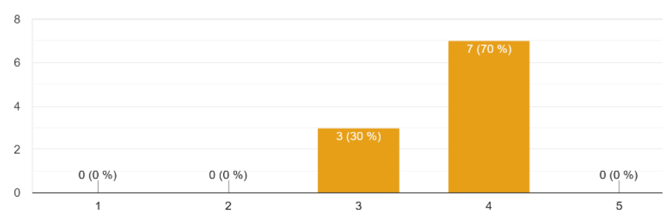

Figure 5. Evaluation of the course difficulty (1 – very easy, 5 - very difficult).

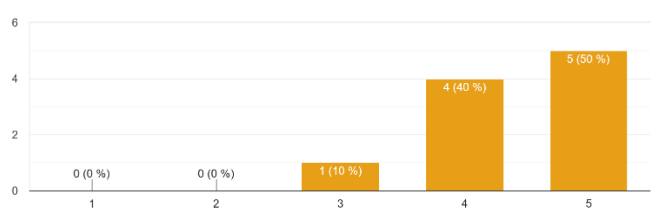

Figure 6. Evaluation of the study literature (1 - worst, 5 - best).

In the third question, we asked students to evaluate the format of the Active tutorial on a scale from 1 (worst) to 5 points (best). Although in this feedback, the evaluation is more distributed, majority, i.e., 70% of students rated the Active tutorial format with 4 points, see Figure 7. There was also the ability to write a comment about the novel format of the lectures. Most of the students were satisfied, but they complained about the increased time they needed to dedicate to the course:

"It was more time-consuming, but I personally liked it because I could take good notes right away. I would probably watch the lectures again before the exam anyway."

"It's very time-consuming, it practically doubles the lecture time, and I only fully understand it in class. The recordings are great - you can always return to the topic, and they complement the lectures in class nicely."

"I prefer it over a regular lecture."

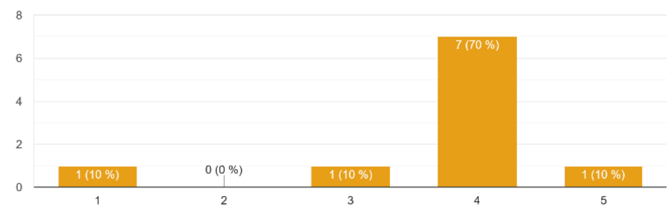

Figure 7. Evaluation of the Active tutorial (1 - worst, 5 - best).

In the last two questions we asked about the seminars. First, students evaluated the format of the seminars on a scale from 1 (worst) to 5 points (best), see Figure 8. Here, students expressed their satisfaction, i.e., 90% of students rated the seminars with 5 points and the rest rated them with 4 points.

Finally, we asked students about their opinion on the ability to work independently during seminars, because our aim was to decrease the necessity to lead the students and to support them mostly in work with MATLAB. The students could evaluate the independence during seminars on a scale from 1 (need for lots of support) to 5 points (totally independent), see Figure 9. The evaluation in this question is distributed, but most of the students, i.e., 60%, evaluated the independency with 3 points. The reason behind this is probably that many students studied bachelor's degrees with mostly chemical backgrounds and with no previous experience with automatic control. Students were able to leave a comment to this question, and support our reasoning of the lack of independence during seminars:

"Many things were new to me and some I barely remembered, so I didn't even know how to start with

some tasks. Some questions were perhaps a little complicated and asked about things I hadn't encountered much before."

"The exercises were great and over time they became easier to understand. At first, everyone is of course a little lost, but over time, people get into it and start to understand the context and connections."

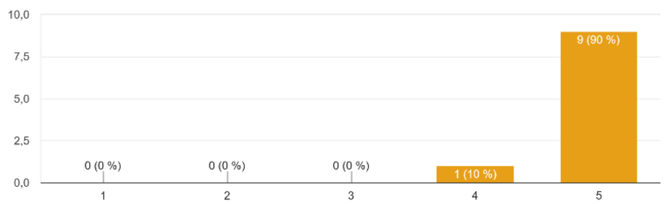

Figure 8. Evaluation of the seminars (1 - worst, 5 - best).

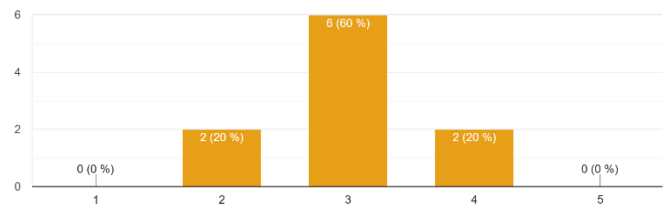

Figure 9. Opinion on independence during seminars (1 - need for lots of support, 5 - totally independent).

To summarize, the students see the course as quite a difficult one. Despite this fact, they rate its quality and study materials highly. The novel format of Active tutorials is more time-demanding, but students prefer it over a standard lecture.

CONCLUSION

This paper presents our experiences and provides an overview of the structure and methods employed to enhance teaching and learning in a master's-level course on automatic control. By leveraging innovative teaching strategies, such as flipped classrooms, active tutorials, real-time experiments, and digital tools like Moodle, we successfully improved the quality of education and student engagement. The course structure integrates mainly theoretical background together with practical applications, supported by comprehensive study materials and hands-on learning through simulations and portable laboratory devices.

The students' feedback indicates a positive response to the novel teaching methods despite the recognized difficulty of the course. Students appreciate the new format, even though it demands significant time and effort. Moreover, introducing the Active tutorials led to improvement in the results of the course weekly survey when comparing this academic year with the previous one.

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