ENGINEERING EDUCATION RESULTING IN SKILLED, INVENTIVE AND INNOVATIVE PROFESSIONALS, HOW?

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ABSTRACT

The use of robots in all areas of production increases continuously. At the same time the robots are used to solve more and more complex tasks. Engineers have to develop, design and implement these complex robots. In this paper we present the idea of combining the theory and exercises with project- and team-work. Our goal is to ensure that the students understand complex and abstract mathematical approach to Control Theory through lectures, simulations, exercises and robot project. Motivation to study mathematical content of control theory increases when theoretical problems are related to robot project and teamwork help them to design working model. However, the future engineers have to deal with problems requiring skills to understand complex abstract mathematical solutions and it is necessary to train students in problem solving. Practical exercises, simulation and project work help them to understand the problems but do not give them necessary training to develop their analytical mathematical skills. The combination of mandatory assignments including mathematical control problems with robot project gives the necessary support to develop students' analytical skills and enhance their understanding of abstract mathematics. Examples of mandatory assignments are given. We also present students' own evaluation of this course.

KEYWORDS

Motivation, Engineering Mathematics, Control Theory, Robot Project, Project Based Learning.

INTRODUCTION

Robotics and control are disciplines presenting numerable challenges and opportunities that impact different aspects of science and technology, from pure theoretical problems to practical challenges and technological demands. Robotics systems often must operate under communication constrains, which require integration and interaction of different components. The engineering task is to ensure that the parts work together to make the functioning system, the robot. Robotic systems include one or more "intelligent" parts, which can compute, reason, or "decide", and this is what control is about. This is very similar to feedback system, but much more complex including interconnection of several feedback systems. Modern control theory is knowledge based on mathematical models and experimental data. Models are usually described in terms of mathematical equations, and for linear models these are linear differential equations. But all real systems include nonlinearities and delays, which make more complex to describe and understand the behaviour of these systems and often require more complex mathematics and physics. Nowadays the systems are built up of several subsystems including all types of components with constrains and the interactions. These are challenges our graduates will meet when working in industry and we need to prepare them to face these challenges. On the other hand control theory is the discipline requiring a solid knowledge of mathematics and when we talk about undergraduate engineering students who do not wish to continue their education

towards Master or Ph.D. degrees, we need to focus on practical aspects of the theory we teach them even more than it is the case with graduate engineering students [1,6,20]. The motivation to learn mathematics must be enhanced in order to succeed in learning and understanding control systems and robotics [3,15,16,24]. The understanding of complex systems is necessary in order to innovate and create technical inventions, and this is the future of engineering [21,23].
Our university, DTU Diplom, Ballerup Campus (previously Copenhagen University College of Engineering) works with CDIO standards. CDIO principles [10,11] fit very well for our engineering students, students wishing integration between the theory and engineering projects and/or experiments.

BACHELOR PROGRAM IN ELECTRONICS AND COMPUTER ENGINEERING

Our Bachelor program in Electronics and Computer Engineering, since 2011, is in the process of adaptation to CDIO standards. However, already 10 years ago we made the major changes in the same program in order to renew the educational methods in our department and we decided to change the study structure towards more projects and teamwork. Similar changes were made for all semesters in our programs including the basic courses in mathematics and physics and other more program specific courses. Our program in Electronics and Information Technology is organized to achieve a balance between subject- and problem-oriented work and between lectures, exercises and team work. Successful cross-college collaboration between faculty members made it possible to develop courses, which combine different engineering disciplines with basic theory. We changed and improved some parts of these programs several times, corresponding to our experiences and students' evaluations. The following shows the contents of the program in Electronics and Information Technology:

- 1st semester: Mathematics with Digital Signal Processing, Object Oriented Programming, Digital Electronics, common project.
- 2nd semester, more advanced: Mathematics with Digital Signal Processing, Object Oriented Programming and Digital Electronics, common project.
- 3rd semester: Electro-physics, Circuit Theory and Analogue Electronics , common project.
- 4th semester: Mathematics with Digital Signal Processing, Mathematical Modeling, Dynamical Systems and Control Theory, project (design, build and program an autonomous robot).
- 5th semester: optional/elective courses.
- 6th semester: optional courses and practical training in a company.
- 7th semester: Bachelor project and practical training in a company.

The structure of Electronics and Computer Engineering program is shown in figure 1.
Our students work from the very beginning (first semester) in groups solving practical engineering problems related to the theoretical subjects [8,9]. The education is described using a study module system. The educational value of a study module is expressed using the European Credit Transfer System (ECTS). The workload of one semester study is equivalent to 30 ECTS credits. In each semester, students work in teams with design projects (usually these are interdisciplinary projects) combining all the theory they have learned in previous semesters and with the focus on theoretical topics covered in courses the have in parallel with their project [9]. The teams consist of 3 to 6 students, depending on particular projects. Each team has a project supervisor - one of the professors involved in the theoretical courses for the particular semester. Each team has to describe the project work, theoretical analysis and final solution of

the problems in short (10-30 pages) reports. They usually present their work to other teams and all the tutors during one or two seminars each semester, and as a part of the examination.

<table>
<tr><th>ECTS</th><th>1. sem</th><th>2. sem</th><th>3. sem</th><th>4. sem</th><th>5. sem</th><th>6. sem</th><th>7. sem</th></tr>
<tr><td>5</td><td rowspan="2">Object Oriented Prog. 1</td><td rowspan="2">Object Oriented Prog. 2</td><td rowspan="2">Circuit Theory</td><td rowspan="2">Control Theory</td><td rowspan="3">Optional courses</td><td rowspan="3">Optional courses</td><td rowspan="3">Bachelor-project</td></tr>
<tr><td>5</td></tr>
<tr><td>5</td><td rowspan="2">Project 1</td><td rowspan="2">Project 2</td><td rowspan="2">Project 3</td><td rowspan="2">Robot project</td></tr>
<tr><td>5</td><td rowspan="3">Optional courses</td><td rowspan="3">Practical Training</td><td rowspan="3">Practical Training</td></tr>
<tr><td>5</td><td rowspan="2">Mat1 (DSM1)</td><td rowspan="2">Mat2 (DSM2)</td><td rowspan="2">Electro-magnetism</td><td rowspan="2">Mat4 (DSM4)</td></tr>
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Figure 1. Electronics and Computer Engineering program

Project- based learning requires a high degree of concentration in particular topics and in order to support this educational method we also changed the weekly time schedule. Students have only two modules/topics during per day, one from 8:30-12 and one from 12:30-16:00. Each module includes four lectures of approximately 45 minutes and some necessary breaks in between. One module of tuition is usually related to a course of 5 ECTS credits, and one module of teacher tuition requires on average 4 hours of self-study for the student.
Major changes of educational structure could be difficult to accept for university teachers/professors, and the most common questions usually are:

1. Can we cover the syllabus?
2. Are the students ready to study independently?
3. Are all the students active in teams?
4. How to manage the conflicts in teams?
5. How to examine and grade the students?

In order to succeed with changes in the program and in educational methods we organize Faculty Seminar varying one to two days approximately once a year, involving all faculty members, teachers, technicians and administration staff. During these seminars we discuss our experiences together with advantages and disadvantages in the structure of our programs, and how to improve them. We have at our university a pedagogical adviser who is involved in development of our programs, and ready to help to solve practical problems when implementing the new program or the changes to existing programs.
Problem oriented education and teamwork increase the motivation of the engineering students for theoretical subjects like: mathematics, mechanics, physics and control theory [2,5,14]. At the same time, almost all engineering jobs require good presentation and communication skills [13]. This includes also the skills to practically apply modern presentation software, like PowerPoint, to present technical aspects in a convincing way to colleagues, to managers, and to customers.

DYNAMICAL SYSTEMS, CONTROL THEORY AND THE ROBOT PROJECT

The Bachelor programs in several areas of engineering like Electrical and Mechanical Engineering, in almost all countries include Control Theory course or courses. The content of those courses varies from one country to another and sometimes from one university to another even in the same country, but in all cases the students have to work with complex systems and abstract mathematics. Training students' mathematical skills is a way to prepare them to analyze engineering problems in their future careers and to draw conclusion in order to find solutions to the complex technical problems. The education in analytical approach to engineering problems enhances students' abilities to innovate and even to get invention's ideas [12,18,22,25,26,26]. In our case, the course in Dynamical Systems and Control Theory – REG4E [7,17,19] includes following:

1. Introduction to Control Systems
2. Differential equations with focus on Laplace Transformation
3. Modeling in the Frequency Domain
4. Modeling in the Time Domain
5. Time Response
6. Frequency Response Techniques
7. Reduction of Multiple Subsystems
8. Stability in time and frequency domains
9. Steady-State Errors
10. Root Locus Techniques
11. Three term - PID controllers
12. The design of feedback control systems in Frequency Domain
13. Digital PID-Controllers

We specified following learning outcomes for REG4E - the student must be able to:

- use concepts, theory, components and methods introduced in the course,
- develop and use mathematical models for technical systems, design and simulate relevant controllers, as introduced in the course,
- design, calculate, and simulate continuous PID-controllers, for different technical systems,
- design and simulate digital PID-controllers, with nonlinearities,
- analyze specifications, calculations and simulations, and draw clear and relevant conclusion,
- hypothesize the reasons for differences between calculated and simulated/actual results and discuss the hypothesis from relevant theory or from relevant simulations and test.

The robot project (PROE4) is closely connected to the course in dynamical systems and control theory where students train and exercise their control theory skills. In PROE4 students design and build the autonomous robot performing tasks where they need to implement control theory. The robot project is an interdisciplinary project including following topics:

- Applied continuous and digital control theory.
- Applied microprocessors and programming.
- Applied digital- and analogue electronics.
- Modeling and simulation in MATLAB and SIMULINK

Learning outcomes - PROE4 trains the students in following skills:

- to plan their own workload,
- to manage engineering design problems from the specification to the working model,
- to manage more than one solution to the design problem,
- to study new subjects independently,
- to keep agreements
- to implement technical solutions into working model
- to communicate clearly both orally and in writing,
- to work with big engineering projects in a team

- to co-operate with others in team.

The robot-project challenges the students to find individual solutions to engineering problems and different robot competitions increase the motivation [4,6]. PROE4 is the integrated project format, where students work in teams. During the project students design and implement an autonomous mobile robot, executing a compulsory task and an optional task chosen by the students. The students work in teams (the project groups), which consist of 4 to 5 students each. The formation of the groups has to be done during the first week of the semester. The formation of the groups is students' own responsibility, because among the objectives of this course are teamwork and cooperation. The robot is a line-following robot, it must be able to follow the specified track on the floor which contains different challenges, like breaks in line, curves and obstacles. We change the track every semester, to prevent copying the solutions from previous semesters. The robot's movement must be stable and smooth. The robot must pass the compulsory task with the highest speed and high accuracy (stay on line during the run).
An optional task or the free task is defined by students. It is a great challenge and gives them freedom to express their own ideas. One of the students' groups made following specification of the optional task [4]:

The optional task defined by this group is based primarily on implementation of a bluetooth module on the robot making it possible to remote control the robot from another bluetooth enabled device and to receive information from the robot. The devices used to communicate with the robot are:

1. *A bluetooth enabled PC running the custom Java program called »Robot Control Center«.*
2. *A bluetooth enabled mobile phone running another custom Java program called »Robot Control Center Phone«.*

The communication protocol created to connect another device with the robot is able to send commands from the connected device to the robot for remote controlling it – the commands determine the speed, direction, etc. on the robot. The protocol is also able to send commands from the robot to the connected device containing information on the battery level, actual speed, motor controller values, etc.
As listed in the following table 1, the group has set a number of requirements to the free task:

Table 1. The free task requirements

Requirement Number	***Specification***
R1	*The robot must implement a bluetooth module and be able to communicate with another bluetooth enabled device such as a PC or mobile phone with a software program able to send and receive commands.*
R2	*The robot must be able to be remote controlled from the connected device.*
R3	*The connected device must be able to receive data from the robot with information about actual speed, battery level, etc.*
R4	*The robot must implement distance sensors to prevent it from crashing into a wall or other objects.*
R5	*Timing issues and improvements of the already implemented parts must be optimized.*
R6	*The robot must be able to switch between the task required for part one and the task required for part two.*

THEORETICAL EXERCISES AND MANDATORY ASSIGNMENTS

During the semester students have to follow Control Theory classes, eight hours a week. Usually the students' own workload is the same as the time used for lectures. Control theory course is 10 ECTS course, lectures and problem work solving, including simulations with MATLAB and SIMULINK. The students have to deliver two mandatory assignments (MA1 and MA2), both assignments are related to the robot project and consist of two parts: the theoretical part and the robot related part. The last three semesters the theoretical parts of both assignments have been extended in order to enhance students' analytical mathematical skills. Our previous experience showed us that though the students were able to calculate, design and build the controllers using the proper mathematical methods, their abilities to solve complex mathematical problems in general was poor. For this reason we decided to extend the theoretical part of the assignments to train students in solving mathematical problems connected to control theory. The assignments are organized as follows:

1. Control Theory Part, problems from engineering practice:
   - explained in words,
   - visualized by pictures
   - shown on block-diagrams

   The solutions have to be supported by simulations in MATLAB/SIMULINK.
2. Robot Part, consist of:
   - Mathematical modeling of the robot
   - Design of P-, PI-, PD- and PID-controllers continuous and discreet.
   - Simulations in MATLAB and SIMULINK

Some examples of visualizing theoretical problems are shown in figure 2. This method gives our students the feeling, that the theory they learn and the problems they solve are close connected to "the real world" engineering problems. The students' motivation to work with mandatory assignments is increased, as the students are very active during the classes and after the classes sending e-mails to us with questions.

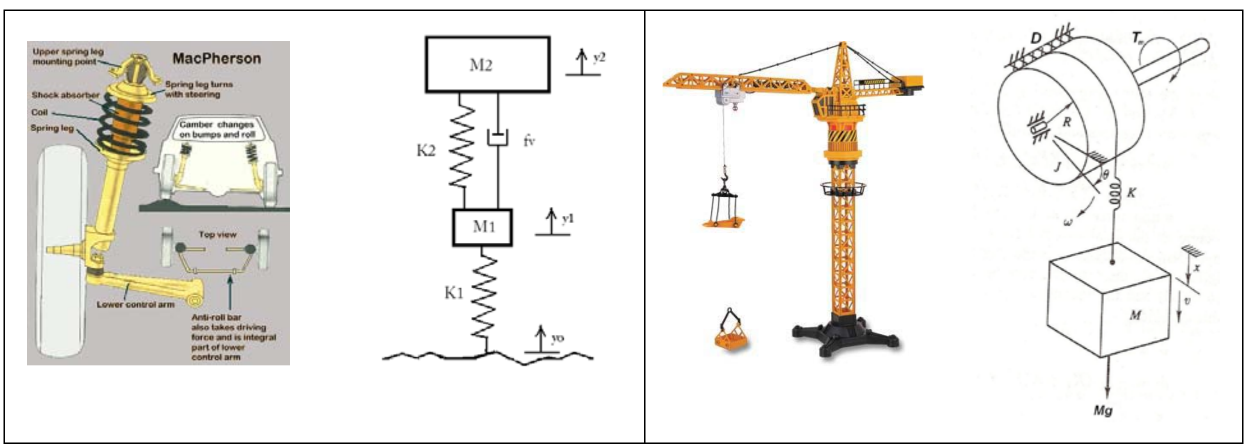

Figure 2. Modeling and simulation of mechanical systems

Students make evaluation of theirs courses twice during the semester, in the middle of the semester (to have the possibility for improvements) and after the examination. The final evaluation, after the examination, is made on CampusNet (Danish developed platform similar to Moodle and Weblearn) and the results of this evaluation are available to the students participating in the course, the teachers and the head of the department. The evaluations include three parts: course evaluation, teacher's evaluation and general comments. Table 2 shows the questions (part of the questionnaire) we used for statistics.

Table 2. The evaluation questionnaire

Course evaluation	
Grading:	**1** (high) **2** **3** (average) **4** **5** (low)
1.	**Target fulfillment:** To what degree has your learning measured up to the course description?
2.	**Your own performance:** How much time do you estimate you have spent on the course compared with the expected time**?**
3.	**The relevance of the course:** To what degree do you consider the course relevant for your education?
4.	**The teaching method:** To what degree has the teaching method supported your learning?
5.	**The test/examination method:** To what degree do you find that the examination method matched the method of teaching?
6.	**The teacher's feedback on student work with assignments etc.:** How do you evaluate the quality of the feedback you received on questions, work with assignments etc.?

In spring 2011 we made major changes to the theoretical part of mandatory assignments for Control Theory course. The results of evaluations are shown in figure 3 for Control Theory course in fall 2010 and in spring 2012. The evaluations have been answered in fall 2010 by 64% of the students and in spring 2012 by 80% of the students.

CONCLUSIONS AND FUTURE WORK

After the last three semesters of completed modified control theory course and robot project course we can make the conclusion, that there is a significant improvement in students' achievements. The students are in general more focused on passing the examination than learning the subject objectives. However the practical approach to the theoretical subjects and close connection to the robot project, which is an "open-end" project giving the students wide range of possible solutions' methods, attribute to a better understanding of complex mathematical and engineering problems. Learning complex mathematical subjects as control theory is not an easy work except for some especially interested students. This was actually the observed situation in the past, when REG4E course was only connected to laboratory exercises. The design and building of the autonomous robot improve students' motivation and understanding of complex mathematics with ability to connect the theory to practical engineering work. Students are also stimulated by "group-behavior principle". They interact with each other and increase their professional performance which is clearly observed in the evaluations (graphs 1, 2, 3 in figure 3). We have also observed the increased interest in automation and robotics, as the growing number of students is looking for internship where they can work with the named issues. The students with previous practical experience show also a significant interest in mathematics and control theory, which was not the case previously. The students' evaluations, shown in figure 3 graph 4, indicate a significant improvement in the students learning as supported by our teaching method. Furthermore the examination method is considered to match the method of teaching, figure 3 graph 5. This study needs to be extended to include two and more detailed questionnaires, one in the middle of the semester and one after the examination, in order to get a better picture of the students' opinion and achievements, compared to the learning outcomes of both courses.

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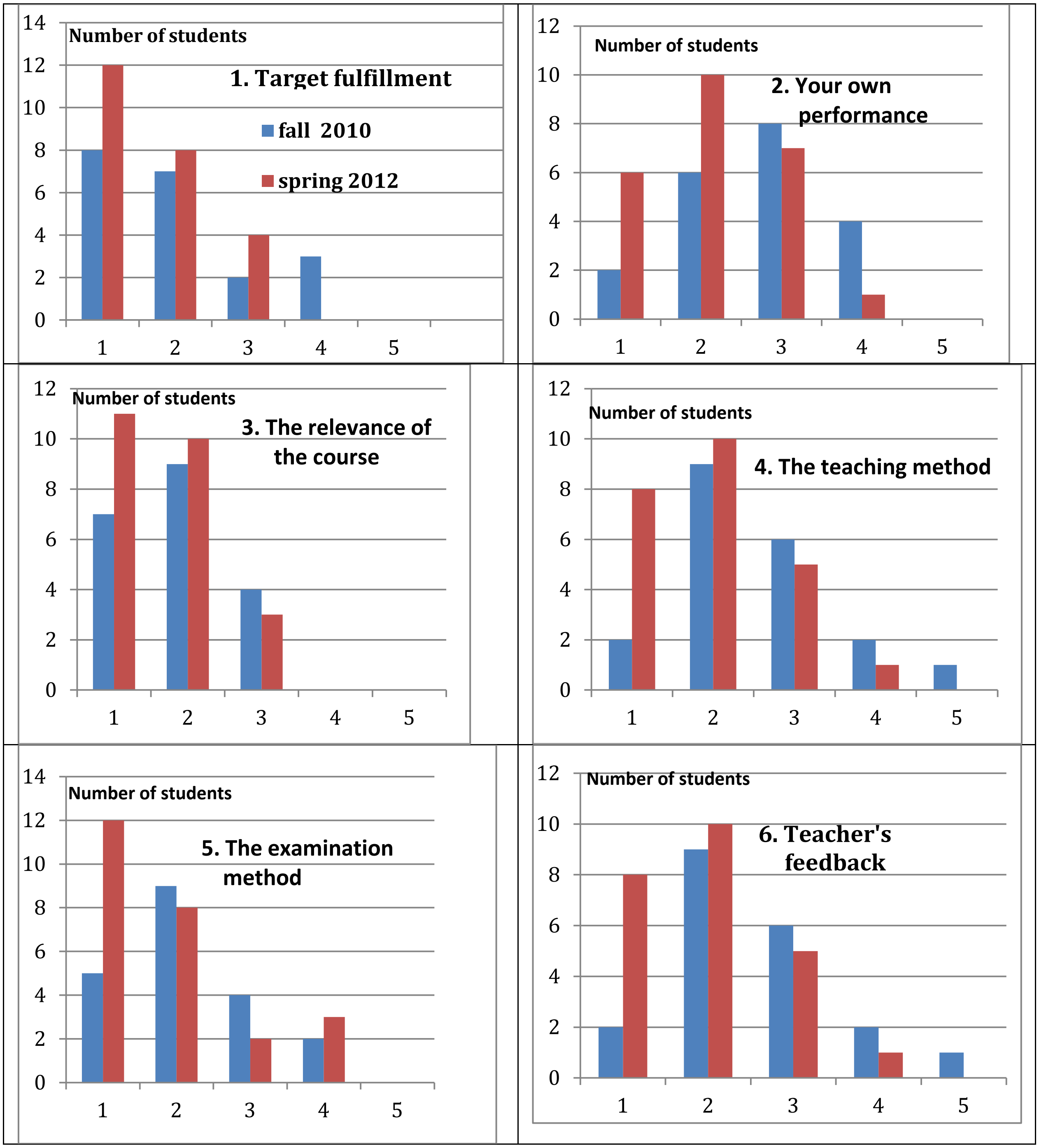

Figure 3. The results of evaluations

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BIOGRAPHICAL INFORMATION

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