INTEGRATING INTRODUCTION TO ENGINEERING LECTURES WITH A ROBOTICS LAB

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ABSTRACT

RWTH Aachen University added an introduction to engineering class in its Electrical Engineering and Information Technology curriculum in 2007. The class combines classic lectures and exercises with an integrated robotics lab. Lectures and exercises focus on mathematical fundamentals of signal processing and provide an introduction to programming with MATLAB®.

The robotics lab is held in groups of 16 to 30 students at different institutes throughout the Department of Electrical Engineering and Information Technology. Teams of two to four students engage in a series of tasks to in which they learn how to use the LEGO® Mindstorms® NXT hardware and MATLAB to control their robots. The tasks are designed to deepen the knowledge presented in the lectures and to connect lecture topics to engineering workflows and problem solving.

The students' final task is to conceive a robot project idea and develop a solution. The students design a multidisciplinary solution that combines hardware assembly and software control to meet the requirements of their project. They then implement this design using the LEGO Mindstorms NXT hardware and the *RWTH - Mindstorms NXT Toolbox* for MATLAB. After testing the implementation to verify its functionality, the teams prepare a talk with accompanying slides and present the project idea they conceived, their design, and its implementation before demonstrating their robot in operation to fellow students and teachers.

In this paper, we describe the design and teaching goals of the introduction to engineering class as well as its integration into the curriculum. We compare our findings to the CDIO standards and the CDIO syllabus 2.0.

KEYWORDS

Introduction to engineering, robotics class, integrated curriculum, LEGO Mindstorms NXT, MATLAB, Standards: 2, 3, 4, 5, 6, 8, and 10.

INTRODUCTION

The Department of Electrical Engineering and Information Technology at RWTH Aachen University developed a first-year class for students to learn fundamental engineering skills. The class consists of regular lectures and exercises as well an integrated robotics lab [Institute of Imaging & Computer Vision, 2007]. The aim of the introduction of the class was to close a perceived gap between the skills students needed to develop for their academic and industrial career and the those fostered by the electrical engineering program at RWTH

Aachen University before 2007. Furthermore, it seemed a great to connect the fundamentals of engineering taught by the early classes with real-world experiences to motivate the students.

Bologna Process

In 1999, 29 European countries agreed to harmonize their academic education systems to increase transparency and foster mobility of students and academics throughout the European Higher Education Area. The agreement was reached and signed in Bologna, and the resulting declaration is known as the Bologna Process. The adoption of this process in Germany forced universities to move gradually from the established diploma system to the internationally prevalent system of bachelor's and master's degrees. During this transition, many university programs changed substantially and large restructuring measures were applied to curricula to comply with new regulations and accreditation requirements.

The Department of Electrical Engineering and Information Technology at RWTH Aachen University reformed its Electrical Engineering and Information Technology curriculum in 2007. Modifications to the curriculum were implemented to comply with modern education standards and to ensure great engineering education for the students. Many classes were changed, some removed, and others newly formed. For example, a mechanical engineering class focusing on covering drilling, screws, fittings, and windings was discontinued in the bachelor's program, freeing time in the first semester. At the same time, other efforts were made to increase the number of graduates and to lower the drop-out rate.

Goals of the introductory class and laboratory

Increase motivation

Studying electrical engineering is a long-term goal. It is important for students to receive positive feedback and to create favorable memories early on. This motivates the students to keep on track and increases their resolve to meet the coming challenges.

Emphasize practical aspects of theory

The first years of engineering education are focused on building a solid foundation of fundamental sciences. Often, students have trouble seeing the value of these theoretical lessons. The department sought to address this by emphasizing the practical aspects of theory.

Overcome shortcomings and differences in mathematical skills

Because students come from different educational systems and schools, they have a wide range of mathematical backgrounds. In Germany, education is the responsibility of the federal states, so even students from the same country can have substantially different knowledge in basic sciences like mathematics. One group of students may already understand complex numbers and have relatively little knowledge of stochastics, while a second group is in the opposite situation. Recognizing and addressing these differences was an important objective at RWTH Aachen University.

Introduce programming

Many first-year engineering students have never written a computer program in any language. Others have been engaged in programming activities in school or as a hobby for years. As with the wide range of mathematical skills among students, it is necessary to address this gap and to bring all students to a level where they can apply practical programming to solve problems they encounter during their first year and beyond.

Foster teamwork

Like first-year engineering classes at many universities, the first-year classes at RWTH Aachen University focus on classical lectures and exercises, with relatively few team activities. However, the department saw it as vital for students to learn teamwork, to tackle challenges cooperatively, and to establish a network of peers, which makes it easy to form study groups and can increase the students' overall satisfaction with their choice of studies.

Analysis with reference to the CDIO standards and syllabus

This paper analyzes the introduction to engineering class at RWTH Aachen University and the learning outcome of the students with respect to compliance with the CDIO standards and syllabus. A second goal is to enable interested parties to benefit from the information and analysis in preparing their own classes and designing curricula for their schools.

Paper structure

The remainder of this paper is structured as follows. The class concept and implementation details are given in second section, "Class Description". The application and mapping of CDIO standards and syllabus 2.0 are discussed in the third section, "CDIO Standards Analysis". The closing section summarizes the findings.

CLASS DESCRIPTION

All students in the first semester of the Electrical Engineering and Information Technology program participate in the introduction to engineering class. Despite high fluctuation in attendance in recent years (2010/2011 – 399 students, 2011/2012 – 536 students, 2012/2013 – 358 students, 2013/2014 – 502) because of modifications to the German secondary education system[1] and the abolishment of compulsory military service in Germany, the class size has always been far too big to work with as a single group.

The class is divided into three parts: a series of lectures, the associated exercises, and the robotics lab. Each week in the semester features two lectures and one exercise. The robotics lab is an eight-day block event. Detailed descriptions of the course design are given by Behrens et al. (2008a, 2008b, 2010a, 2010b, 2011).

Lectures

The lectures are provided in a class titled *Mathematical Methods of Electrical Engineering*, which focuses on mathematical concepts that are essential for electrical engineering students. The covered topics were selected in cooperation with other members of the department's faculty and include complex numbers, solving systems of linear equations, and matrix calculations as well as signal processing basics such as sinusoidal signals, Fourier transforms, spectral analysis, and sampling. Topics were selected to complement the regular mathematics classes and to facilitate a seamless move from secondary education to electrical engineering studies.

[1] Several German Federal States (including North Rhine-Westphalia (NRW), where RWTH Aachen University is located) changed from 13 to 12 years of school.

Furthermore, students in the class learn programming with MATLAB. MATLAB is a standard industry tool for mathematical computing and widely used throughout academia for teaching and research. Students benefit from MATLAB programming knowledge immediately in their first-year studies, in their future academic studies at RWTH Aachen University, and in their careers in industry or academia.

Exercises

In carefully planned exercises, students perform calculations and solve simple tasks with MATLAB. Introductory and advanced assignments are an opportunity to reinforce and supplement the mathematical concepts and programming approaches presented during the lectures.

Robotics lab

The robotics lab class, *MATLAB meets LEGO Mindstorms* (Institute of Imaging & Computer Vision, 2007), is designed as a block event scheduled in mid-December. In a period of eight days, students solve engineering challenges with MATLAB, RWTH - Mindstorms NXT Toolbox for MATLAB [RWTH Aachen University, 2007], and LEGO Mindstorms NXT robots. They engage in group work and discussions and give a final team presentation.

Student Groups

The lab class is a prerequisite for all first-year students in the Electrical Engineering and Information Technology program. Each institute of the Department of Electrical Engineering and Information Technology is in charge of one group of students. This distribution of effort enables all students to take the class in parallel during the same eight days. Groups of 16-30 students, depending on room sizes and other logistical parameters, are usually guided by a PhD student and up to three graduate student teaching assistants.

Course Timetable

An example timetable for the MATLAB meets LEGO Mindstorms lab class is shown in Figure 1. This schedule was used in the winter term of 2012/2013.

The students spend the first 4.5 days learning how to use the LEGO Mindstorms NXT hardware and peripherals. For example, the first session focuses on the *brick*, the main

	Morning	Afternoon
Day 1	NXT	Bluetooth connection + Tactile Sensor
Day 2	Sound Sensor	Motors
Day 3	Motors	Optical Sensor
Day 4	Optical Sensor	Ultrasonic Sensor
Day 5	Ultrasonic Sensor	Group Project
Day 6	Group Project	Group Project
Day 7	Group Project	Group Project
Day 8	Group Project	Final Presentation

Figure 1 Example timetable for the MATLAB meets LEGO Mindstorms robotics lab

component of every robot. The second session covers the essential Bluetooth connection between the brick and the host computer. Motors as well as tactile, sound, optical, and ultrasonic sensors are introduced in the following days. Teams of two students complete activities using a LEGO Mindstorms NXT set and a computer running MATLAB.

Where feasible, lecture topics are revisited and serve as the theoretical foundation for lab activities. The motor task, for example, involves addressing the hardware using complex numbers and the sound sensor task builds upon signal processing basics covered in lecture.

The group project phase spans the next three days. Two-student teams combine to form groups of four students. Their hardware is pooled for the group as well. With the additional possibilities, students conceive their own challenge and design a creative solution using their knowledge of MATLAB and LEGO Mindstorms NXT hardware. Under the guidance and supervision of the staff, the students implement their robot and create a presentation, which they deliver in the final session, presenting their robot to the other participants with a talk and a live demonstration.

Hardware and Software Requirements

Each team of two students has access to a computer on which MATLAB and the RWTH LEGO Mindstorms NXT toolbox is installed.

The computers used for the lab are used for other activities during the rest of the year (for example, they are used in student labs or as workstation for thesis preparations).Class organizers created a bootable DVD with a LINUX operating system and the necessary software to participate in the class. With this DVD, a lab computer can be used for the *MATLAB meets LEGO Mindstorms* class without any changes to its hard drive, and it can immediately be returned to its normal operation after the eight-day class has ended.

The teams also receive a LEGO brick and a set of peripherals for their tasks. A set of two LEGO Mindstorms NXT boxes (base and extension pack) contain all necessary parts for the lab. Student teams are permitted to share their resources with other teams, making it possible to build even more sophisticated robots.

Student Preparation

Students must pass a MATLAB exam before they can participate in the *MATLAB meets LEGO Mindstorms* robotics lab class. It is imperative for the success of the group and the individual, that all students have acquired the MATLAB skills needed to complete the tasks.

The multiple choice exam can be taken online for about three weeks prior to the class. A student has three attempts to pass the exam. Usually, most students pass the test in time. A few students, mostly due to neglect or technical difficulties, fail to complete the test. These students are invited to retake the test in a special session under the supervision of experienced tutors. Most students manage to pass the test comfortably and almost all are cleared to participate in the lab class.

MATLAB Team Award

Every year, a group of tutors and sponsors selects the best student project of that year. The students who built the winning project are invited to present their robot with a video and short talk at the department’s annual convention. They also receive the MATLAB Team Award for their efforts. Winning robots from recent years can be seen on the university’s website [Behens, 2008a, 2008b].

Lab Course Evaluation and Feedback

Students are given the opportunity to provide feedback on the class each year. They are asked to answer multiple choice questions, rate different aspects of the class, and give free-text feedback as well. The questions cover their overall satisfaction with the class, their learning experience, the performance of the tutors, and the hardware among other topics. A selection of questions and answers from the students and a more detailed report of recent survey findings can be found in [Gross, 2014].

CDIO STANDARDS ANALYSIS

The design and implementation of the introduction to engineering class at RTWH Aachen fulfils many goals of the CDIO standards and syllabus.

CDIO Syllabus Outcomes (Standard 2)

The introduction to engineering class has numerous teaching goals that can be mapped to the CDIO syllabus 2.0.

1. Disciplinary Knowledge and Reasoning

As an introductory class, the class focuses on underlying knowledge (1.1) in mathematics (1.1.1) and core engineering fundamental knowledge (1.2) especially in the field of signal processing during the lectures and exercises. The practical lab tasks revisit this knowledge to deepen and intensify the learning experience.

2. Personal and Professional Skills and Attributes

The robotics lab portion of the class provides new learning avenues in addition to traditional lectures and exercises. Analytical reasoning and problem solving (2.1) are key elements in the creative task completed during the last three days of the lab class. The students are encouraged to choose and formulate their own problem (2.1.1) and to create a model (2.1.2) for it. Some groups must complete considerable analysis (2.1.3) to understand their problem in its entirety and often experience new challenges while doing so. The limited accuracy of LEGO sensor readings and mechanical stiffness properties of LEGO construction elements impose significant constraints that need to be identified and understood. These constraints and uncertainties (2.1.4) have to be considered when the teams come up with a design (2.1.5).

Experimentation, investigation, and knowledge discovery (2.2) are essential for the students to solve both the predefined assignments and their own creative robot design and implementation. Within this context, hypothesis formulation (2.2.1) is especially relevant in the self-defined task. Small experiments may be needed to describe the problem correctly (2.2.3).

System thinking (2.3) is fundamental in the design of a complete system. A holistic approach (2.3.1) is necessary to imagine the final robot. The students have to understand the interactions between different mechanical and electrical parts as well as interaction and abstraction in the program code (2.3.2). Time constraints and the limited hardware at hand require prioritization, focus (2.3.3), trade-offs, and judgments (2.3.4) while modelling a solution and implementing necessary and desired features.

Section (2.4) of the syllabus 2.0 focuses on attitudes, thought, and learning. The student groups imagine and create inventive robots when given enough creative space. In a very short time, they make decisions (2.4.1) concerning their project and commit themselves, individually and as a team, to deliver a solution (2.4.2). The setup encourages each student to contribute to their group's success. Creative (2.4.3) and critical thinking (2.4.4) are a natural part of the process. Many groups use ideas from their personal background, hobbies, and experiences to come up with or implement their robot projects (2.4.5). Furthermore, many students experience a new and creative learning environment and get to know their classmates. This will likely influence their future learning activities and lead to changes in their behavior towards both fellow students and teachers (2.4.6). Time and resource management (2.4.7) are also critical factors. The teams need to partition their project into different tasks that must be managed, engaged in parallel, and finished, with the results integrated into the final robot in three days.

Ethics, equity, and other responsibilities (2.5) are also involved during the lab class and the teamwork. Some groups are multicultural, and students have a range of different backgrounds. Equity and diversity (2.5.5) are especially important in those teams. All students, however, learn about the importance of trust and loyalty to their team (2.5.6).

3. Interpersonal Skills: Teamwork and Communication

Teamwork (3.1) is essential for the group projects. Teams form quickly (3.1.1) and there is little time for establishing formal team operations. Still teams experience many aspects of team operation, including planning, setting team internal rules, giving and receiving feedback, conflict mediation and negotiation, and finding common goals (3.1.2). Teams implicitly or explicitly form a structure and individual members often step up to take the role of a leader (3.1.4).

The requirement to give a presentation to their fellow students and tutors forces the teams to decide on a communication strategy (3.2.1) and to prepare a slide set (3.2.4) for their project. They communicate via graphs and other media (3.2.5) in their oral presentation (3.2.6). During the entire team phase, students need to listen and keep up a constructive dialogue (3.2.7). Naturally, conflicts and different points of view arise. Teams have to debate and compromise (3.2.8) to resolve conflicts and get on with their project. This requires each member of the team to clearly state their point of view (3.2.9). Although there is a required language course for all foreign students, some teams include members who are not fluent in German and it may be beneficial to use English or other languages to communicate among the team (3.2.10).

4. Conceiving, Designing, Implementing, and Operating Systems

The students conceive a problem or task and engage in system engineering (4.3) to set their team's goals and understand the requirements and constraints (4.3.1). They have full flexibility to use the available LEGO hardware and their MATLAB skills to define their system concept and architecture (4.3.2). This has to be engineered and subdivided into different subsystems (4.3.3) that are interconnected with compatible interfaces.

Designing (4.4) a robotic system requires discussing different approaches and an iterative process to come up with prototypes that often evolve as the implementation process uncovers new problems or opportunities (4.4.1). The students learn disciplinary design (4.4.4) when applying their knowledge and tools to create a robot for their task. Furthermore, they model, test, and refine their design to optimize it.

The implementation process (4.5) is divided into two parts. The first is the construction of the mechatronic robot (4.5.2), in which the assembly of different parts, the imprecision of LEGO toys, and the tolerances of movable constructs all play an important role. The second is the software implementation process (4.5.3), which requires the subdivision of a main idea into different functional units, functions, classes, and entities. The teams gather valuable information from tests and verification of their system's performance (4.5.5).

The video of the robot in operation (4.6) and the presentation for peers also serve as preparation for providing operation guidelines and end-customer training (4.6.2).

Integrated Curriculum (Standard 3)

During the redesign of the Electrical Engineering and Information Technology bachelor's degree program at RWTH Aachen University, some content was removed from the curriculum and the new introduction to Engineering class was specifically designed to help students succeed in their first semester and beyond.

The class develops necessary technical skills like mathematics, signal processing, and MATLAB programming as well as personal, interpersonal, and system building skills as referenced in the previous section (Standard 2). The class description for the lab class lists the following learning goals:

- Mathematical methods of signal processing
- Design and implement programs and graphical user interfaces with MATLAB
- Create complex algorithms for robot control
- Teamwork, organization, peer learning, and debate
- Presentation skills

Introduction to engineering (Standard 4)

As mentioned in the previous section, the class *Mathematical Methods in Electrical Engineering* and the associated lab class were created as an introduction to the engineering discipline with an emphasis on problem solving, design exercises in teams, and system building as well as the fostering of personal and interpersonal skills and attitudes.

Design-Build Experiences (Standard 5)

The lab class provides students with the design and implementation experience of building a robot to solve a problem chosen by the team. The class supports this central aim of CDIO to help students identify the connection between their study of fundamental engineering principles and their career path in engineering.

CDIO workspaces (Standard 6)

The students (more than 500 in the winter term 2013/2014) are divided and hosted by different institutes of the Department of Electrical Engineering and Information Technology at RWTH Aachen University to make efficient use of the available infrastructure. This arrangement enables the program to provide three to four tutors per group of 16-30 students and ample space for groups so that students can move around, discuss issues, test their designs, and work flexibly during the project.

Students can also make use of several learning rooms equipped with computers throughout their bachelor's, master's, and PhD degree studies. They may also use a large pool of computers and they are licensed to obtain the latest engineering software such as MATLAB and Simulink® for campus and home use at no charge.

Active Learning (Standard 8)

The learning environment in the robotics lab class is collaborative and students have to engage the different tasks in small groups. The feedback questionnaire completed by the students reflects a high level of student satisfaction with the course [Gross, 2014]. In their feedback, students regularly cite their learning successes and increased motivation as well as positive experiences gained and shared during the course.

Enhancement of Faculty Teaching Skills (Standard 10)

The involvement of all institutes of the Department of Electrical Engineering and Information Technology in the teaching process of the robotics class resulted in a rapid dissemination of teaching knowledge and methods among the department. Teachers of upper-level courses in the curriculum also learn to rely on the fundamentals taught during the introduction to Engineering class. This is true for the disciplinary knowledge as well as MATLAB know-how and teamwork skills. The student teaching assistants are required to participate in a teaching class prior to engaging in their jobs. This class advances their personal teachings skills and, indirectly, the experience of the robotics class participants. Engaging in the class again from a different perspective also helps the student teaching assistants remember and use the basics skills they learned previously.

SUMMARY

The *Mathematical Methods of Electrical Engineering* class and the integrated *MATLAB meets LEGO Mindstorms* lab introduction to engineering at RTWH Aachen achieve a wide range of disciplinary and interdisciplinary learning goals as listed in the curriculum course description. In this paper, we matched those goals explicitly listed and others implicitly present in the class design and implementation to the CDIO syllabus 2.0. Furthermore, we applied the CDIO standard and compared the course design to them. We found a high level of agreement. The concept, therefore, complies with many of the properties of modern, high-quality engineering education as defined by the CDIO.

No single class addresses every aspect of the CDIO standards or syllabus 2.0, but the combination of *Mathematical Methods of Electrical Engineering* class and *MATLAB meets LEGO Mindstorms* serves as a perfect example for the postulated introduction to engineering class (Standard 4). We believe that the concept can serve as an ideal cornerstone for an integrated CDIO curriculum.

REFERENCES

Behrens A., Atorf L., Schwann R., Ballé J., Herold T., Telle A. (2008a). “Practicing Engineering in a First-Year Student Project: MATLAB meets LEGO Mindstorms”, Proceedings of the 12th International Student Conference on Electrical Engineering POSTER 2008, Prague.

Behrens A., Atorf L., Schwann R., Ballé J., Herold T., Telle A. (2008b). “First Steps into Practical Engineering for Freshman Students Using MATLAB and LEGO Mindstorms Robots,” Acta Polytechnica Journal of Advanced Engineering, vol. 48, no. 3, pp. 44-49.

Behrens A., Atorf L., & Aach T.(2010a). “Teaching Practical Engineering for Freshman Students using the RWTH - Mindstorms NXT Toolbox for MATLAB”, in MATLAB - Modelling, Programming and Simulations, E. P. Leite, Eds. SCIYO, pp. 41-65.

Behrens A., Atorf L., Schwann R., Neumann B., Schnitzler R., Ballé J., Herold T., Telle A., Noll T.G., Hameyer K., & Aach T. (2010b). “MATLAB Meets LEGO Mindstorms - A Freshman Introduction Course Into Practical Engineering”, IEEE Transactions on Education, vol. 53, no. 2, pp. 306-317.

Behrens A., & Aach T. (2011). “MATLAB meets LEGO Mindstorms”, Praxiseinblicke - Forschendes Lernen in den Ingenieurwissenschaften, U. Bach, K. Müller, and T. Jungmann, Eds. TeachING-LearnING.EU, pp. 32-35.

Gross S., Kim M., Schlosser J., Lluch D., Mohtadi C., Merhof D., & Schneider D. (2014). Fostering Computational Thinking in Engineering Education - Challenges, examples, and good practices. Proceedings of IEEE EDUCON 2014, Barcelona, Spain, to appear.

Institute of Imaging & Computer Vision (2007). MATLAB meets LEGO Mindstorms, http://mindstorms.lfb.rwth-aachen.de/index.php/en, accessed 12/13/13.

Institute of Imaging & Computer Vision (2009). Team Award Winner 2009. http://mindstorms.lfb.rwth-aachen.de/index.php/de/news/1-aktuelle-nachrichten/313-matlabteamawardpreistraegerws0910, accessed 10/28/2013.

Institute of Imaging & Computer Vision (2011). Team Award Winner 2011. http://mindstorms.lfb.rwth-aachen.de/index.php/de/news/3-kurzmeldungen/421-team-award-gewinner-winter-201112, accessed 10/28/2013.

Institute of Imaging & Computer Vision (2012). Team Award Winner 2012. http://mindstorms.lfb.rwth-aachen.de/index.php/de/news/1-aktuelle-nachrichten/352-team-award-gewinner-winter-201213, accessed 10/28/2013.

RWTH Aachen University (2007), RWTH – Mindstorms NXT Toolbox for MATLAB, http://www.mindstorms.rwth-aachen.de/, accessed 12/13/13.

BIOGRAPHICAL INFORMATION

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