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Automatic Control Education in a CDIO Perspective

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Abstract: The CDIO framework for development of engineering education is presented, including the overall ideas, the fundamental documents, and some development tools. The automatic control subject and its role in engineering education is studied using the CDIO Standards as reference. Some examples from the engineering education at Linköping University are presented with special focus on the control education.

Keywords: The CDIO framework, the CDIO Standards, active learning, design-implement experiences

1. INTRODUCTION - WHAT IS CDIO?

The question of what CDIO stands for and is about can be answered in some different ways. Depending on the viewpoint one can answer the question by saying that CDIO stands for:

- An international collaboration network - The CDIO Initiative. The network will be described in some detail in Section 2.
- A framework for development of engineering education. A general overview of the framework will be given in Section 3.
- An acronym: Conceive, Design, Implement, and Operate. The four words are meant to represent the entire life-cycle of a product or a system, from idea, via construction and implementation to the operation.
- Structured common sense. Few of the components within the CDIO framework are entirely new, and most of the questions and component have been discussed before the formation of the CDIO Initiative. A key feature of CDIO is however that the various components have been put together in a structure, which is valuable and useful for the development of engineering education.

The aim of the paper is to describe how the automatic control subject and the CDIO framework fit together in engineering education. It will be illustrated that control, and various learning activities connected to the subject, fit very well together with several of the CDIO Standards. In addition, it will be illustrated how the control subject with system thinking and a solid understanding of the feedback principle is useful for management and development of engineering education programs. Other examples of how the control subject can be combined with the CDIO framework are given in e.g. Wang et al. (2015) and Gallagher and Goodwine (2012).

The paper is organized as follows. Section 2 gives a brief description of the international network around the CDIO framework, and Section 3 describes the framework. Section 4, which is the main contribution of the paper, describes how the control subject connects to the twelve points of the CDIO Standards. Finally Section 5 contains some conclusions.

2. THE CDIO INITIATIVE

The CDIO Initiative started in 2000, and from the beginning there were four universities involved, three universities in Sweden (Royal Institute of Technology, Chalmers Institute of Technology, and Linköping University) and MIT from the USA. During the first five years the CDIO Initiative was a development project with working groups dealing with the sub-projects Curriculum design, Teaching and learning, Workspaces, and Assessment. Over the years a large number of universities have joined the CDIO Initiative, and it has become a network of collaborating institutions. For the moment there are more than 100 collaborating universities from all over the world. In 2005 the International CDIO conference was held for the first time, and it is now an annual event. An overview of the CDIO Initiative can be found via the web site The CDIO Initiative (2016), where a list of the participating universities and a large number of documents and publications can be found. A thorough presentation of the CDIO framework and some of the main results from the activities within the Initiative are given in Crawley et al. (2014).

3. THE CDIO FRAMEWORK

The CDIO framework can be seen as consisting of four main components:

- A definition of the role of an engineer.
- Clearly defined and documented goals for the desired knowledge and skills of an engineer (The CDIO Syllabus)
- Clearly defined and documented goals for the properties of the engineering education program (The CDIO Standards)
• An engineering approach to the development and management of education programs.

3.1 Definition

The starting point for the CDIO framework is a characterization of what is meant with and expected from a person graduating from an engineering education program. Even though it is not a definition in the normal mathematical sense the term will be used here. In Crawley et al. (2014), page 50, it is stated that:

“Every graduating engineer should be able to:

Conceive, Design, Implement and Operate complex value-added engineering products, processes and systems in a modern, team-based environment.”

Of course, the definition can be discussed in many ways, but provided it is adopted, a natural consequence is to design and develop the engineering education with this definition in focus.

3.2 The CDIO Syllabus

The second component of the CDIO framework consists of specifications of the desired knowledge and skills of a graduating engineer so that they match the definition above. The document can be found via The CDIO Initiative (2016). The web site also contains translations of the document to several other languages. The CDIO Syllabus is structured in the following four main sections:

1 Technical knowledge and reasoning.
2 Personal and professional skills and attributes.
3 Interpersonal skills: Teamwork and communication.
4 Conceiving, designing, implementing and operating systems in the enterprise and societal context.

The document has sub-sections and sub-sub-sections, and it is hence an extensive list of desired knowledge and skills of a graduating engineer. The main efforts within the Initiative have been spent on finding ways to develop and improve the engineering education with respect to sections 2 - 4 of the Syllabus. The document is a useful tool as a framework for specifying learning objectives of both individual courses and entire education programs. There are a number of documents over the world with similar purpose, and one example is the ABET criteria used in the US and elsewhere. The connections between the CDIO Syllabus and the ABET criteria are investigated in e.g. Crawley (2002).

3.3 The CDIO Standards

Assume now that the definition in Section 3.1 has been adopted and that the desired knowledge and skills have been specified using the CDIO Syllabus as reference. The next task is then to specify the desired properties of an engineering education program such that it gives the possibilites for students to reach the desired goals. The third component hence consists of a specification of the desired properties of an engineering program. This document, which is called the CDIO Standards and can be found via The CDIO Initiative (2016), consists of twelve points that define the desired features of the education program from different viewpoints:

1 The context.
2 Learning outcomes.
3 Integrated curriculum.
4 Introduction to engineering.
5 Design-implement experiences.
6 Engineering workspaces.
7 Integrated learning experiences.
8 Active learning.
9 Enhancement of faculty competence.
10 Enhancement of faculty teaching competence.
11 Learning assessment.
12 Program evaluation.

The CDIO Standards will be discussed thoroughly in Section 4. It can also be noted that in several ways there are close connections between the CDIO Standards and the items in the European Standards and Guidelines (ESG) framework for quality assurance. See ESG (2016).

3.4 Engineering approach

The fourth component of the CDIO framework is that it involves an engineering approach to management and development of education programs. This statement can be justified in some different ways as follows:

• The fundamental documents in the framework, the CDIO Syllabus and the CDIO Standards, can be seen as requirement specifications concerning the knowledge and skills of the graduates and of the components of the education programs respectively. By comparing the requirements and expectations with the current situation areas of improvement can be identified.

• A useful tool in the process of setting up goals for knowledge and skills for a particular education program is the Syllabus Survey, which is described in e.g. Bankel et al. (2005). The key idea is to define a set of stakeholders, who have interest in the contents and outcomes of the particular program. This can include alumni, teachers, students, persons in industry with recruiting functions, etc. The stakeholders are then asked to grade the importance of the different subsections (level x.y) of the Syllabus. It is suggested that the grading is done using the following expected levels of proficiency:

    1 To have experienced or been exposed to.
    2 To be able to participate in and contribute to.
    3 To be able to understand and explain.
    4 To be skilled in the practice or implementation of.
    5 To be able to lead or innovate in.

The outcome of the survey can then be used as basis for the design and development of the program. The tool is also described in Chapter 3 of Crawley et al. (2014).

• Also the CDIO Standards can be used as a systematic tool for program evaluation. The idea is to let a group of people responsible for a particular education program carry out a self-evaluation of the program with respect to the twelve items in the Standards and set a grade for each standard according to some
suitable scale. The procedure is described in detail in e.g. in Gray (2011) and Chapter 9 of Crawley et al. (2014), where Table 9.2 presents generic rubric for self-evaluation. The lowest level, corresponding to grade zero, is described “There is no documented plan or activity related to the standards”, while grade five is described “Evidence related to the standard is regularly reviewed and used to make improvements”. By carrying out the self-evaluation with some years time interval signs of improvement should hopefully be visible.

4. CONNECTING THE AUTOMATIC CONTROL SUBJECT TO THE CDIO STANDARDS

This section will connect the automatic control subject to the items in the CDIO Standards presented in 3.3. It should be stressed that the Standards refer to desired properties of the entire engineering education program, and it is hence natural that a specific subject has closer connections to some of the items. The twelve standards have an internal structure, which is indicated by the subsections below.

4.1 The Context

**Standard 1 - Adoption of the principle that product, process, and system lifecycle development and deployment – Conceiving, Designing, Implementing and Operating – are the context for engineering education.**

The standard is tightly connected to the definition stated in Section 3.1, and the interpretation of the standard is that the entire organization around an education program, i.e. people, documents, etc, should have this definition in focus. The control subject fits well in this context, and in a small scale it is possible to cover all four CDIO stages, from an idea or identified needs, via modelling and control design, to implementation, test, and operation.

4.2 Curriculum Design

**Standards 2 - 4 deal with various aspects of the design of the curriculum of an engineering education.**

**Standard 2 - Specific, detailed learning outcomes for personal and interpersonal skills, and product, process, and system building skills, as well as disciplinary knowledge, consistent with program goals and validated by program stakeholders.**

These are general aspects of how an engineering education program is designed and how the different learning outcomes in the CDIO Syllabus are covered in the various courses that together form the entire education program. The validation by program stakeholders, mentioned in the last sentence, can be carried out e.g. via the Syllabus Survey discussed in Section 3.4 or via an organization of the program management such that e.g. industry and students are represented.

**Standard 3 - A curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, and system building skills.**

One property of the control subject is that it relies on good mathematical knowledge from previous courses. The mathematical models and tools in a basic course in automatic control normally involve calculus (differential equations and integrals), linear algebra, and transforms, and on a more advanced level probability and optimization are useful mathematical tools. In addition, basic knowledge in various parts of physics (for the modelling aspects) and programming is required. It is hence important that the interfaces between the mathematics courses and the control courses are designed accordingly.

A useful exercise in order to investigate to what extent the interfaces between individual courses are well designed is to carry out the “Black box exercise” described on pages 106-107 of Crawley et al. (2014). In this exercise each course is seen as a black box where the inputs correspond to the prequisities from previous courses and the outputs correspond to the learning outcomes from the particular course. The exercise can be described schematically as in Figure 1. It can be very useful and productive to gather the teachers responsible for the various courses in a program and let them carry out the exercise at the same time, and then also let them discuss with the teachers responsible for course “before” and “after” in the curriculum. It can then be clarified if the interfaces between the various courses are appropriate or if they need to be adjusted in terms of learning outcomes.

![Fig. 1. Black box exercise: The input arrows to a course represent the expected knowledge skills (prerequisites) from previous courses, and the output arrows represent the expected learning outcomes from the course.](image-url)

**Standard 4 - An introductory course that provides the framework for engineering practice in product, process, and system building, and introduces essential personal and interpersonal skills.**

The motivation for having an introductory course early in the curriculum is that the students in many cases have vague knowledge of what engineering is about. A good introduction to the engineering field could then serve as an inspiration and motivation for further studies. Several such courses have been introduced within the CDIO Initiative, and of course elsewhere. A number of examples can be found via the Knowledge library at The CDIO Initiative (2016). Pages 112-113 of Crawley et al. (2014) give a brief description of such a course, which is part of the curriculum for the Applied physics and electrical engineering program at Linköping university. Some facts about the course:
- The course gives 6 ECTS credits, and it runs over the entire fall semester of year one.
- The course starts with a series of introductory lectures dealing with group dynamics, written and oral communication, the use of a project model, and career examples presented by alumni.
- The main part of the course consists of a project in which the students are expected to develop a product or system given a requirement specification. Referring to Figure 2 it means that the work starts at Tollgate 1 (TG1) with a given requirement specification. The project task includes to develop a project and time plan, where the task is divided into sub-task distributed between the group members.
- The course ends with a project conference where the students present their project results in a conference like format.

The Division of Automatic Control has taken part in this course since its start by offering one of the project tasks. The task is handled by two groups with six students in each group, and the task is to develop a relatively simple autonomous vehicle using Lego Mindstorms.

### 4.3 Design-Implement Experiences and Workspaces

**Standard 5 - A curriculum that includes two or more design-implement experiences, including one at a basic level and one at an advanced level.**

Various types of project courses, where the aim is to develop and build different types of systems, have existed for a long time in engineering education. An important aspect of the CDIO framework is that Standard 5 gives this type of courses, denoted design-implement experiences, a very clear role with clear objectives in the engineering education. In the redesign of the engineering program Applied physics and electrical engineering, reported in Gunnarsson et al. (2005), such courses were introduced at two different stages in the program. In the third year a design-build experience in electronics was introduced, and this course is described in detail in Svensson and Gunnarsson (2012). The aim in this course is to build computer controlled devices and in many of these control is an important enabling technique. In the fifth year of the program a set of ten different design-build experiences was introduced, and the students choose one of those, depending on the chosen specialization. The Division of Automatic Control is responsible for one of these courses, and each year there are approximately 40-50 students following this course. A brief description of this course and examples of a project tasks are given in Enqvist et al. (2005) and Karlsson et al. (2006).

**Standard 6 - Engineering workspaces and laboratories that support and encourage hands-on learning of product, process, and system building, disciplinary knowledge, and social learning.**

In order to be able to include design-implement experiences and active learning in the education it is necessary to have suitable engineering workspaces. In addition to the importance of the workspace itself and the equipment, another important aspect is the access for the students to the workspaces. This depends on the particular subject, related equipment, and safety issues, but full access to the workspaces 24/7 is an important enabler for active learning. One excellent example of an engineering workspace is Muxen, which is used in the design-implement experience in electronics, which is described briefly under Standard 5 and in Svensson and Gunnarsson (2012). In that course the students get full access to the workspace after Tollgate 2, see Figure 3, has been passed.

The various courses in control use the workspace Laboteket (the name is composed of the Swedish words for laboratory and library), and in all courses the students have full access to the workspace from the start of the course. One example of how this can be used in presented in Gunnarsson et al. (2016), which describes a course in which the entire assessment is based on three large laboratory exercises. The duration of each laboratory exercise can be up to two weeks. In two of the laboratory exercises the equipment is comparatively simple, and it consist of a double tank process, a commercial PLC (Programmable Logic Controller), and a desktop PC. The task is to design and implement a process control system, including a operator interface, and to write a manual for the operator. The laboratory exercise starts by a scheduled introduction, and after that the students are expected to plan their work and find suitable time slots in their calendars for carrying out the task. This type of learning activity requires that the students have full access to the workspaces. The third laboratory exercise uses the Lego factory shown in Figure 2.

![Fig. 2. Lego factory.](image)

Also in this case the laboratory exercise starts with a scheduled introduction, and thereafter the students are supposed to carry out the task in an independent way, which requires full access to the workspace and the equipment.

### 4.4 Teaching and Learning

**Standard 7 - Integrated learning experiences that lead to the acquisition of disciplinary knowledge, as well as personal and interpersonal skills, and product, process, and system building skills.**

Design-implement experiences of the type described in connection to Standard 5 offer excellent possibilities for
integrated learning. As pointed out in Svensson and Gunnarsson (2012) the learning outcomes of the course described in that paper address all four sections of the CDIO Syllabus. In a summarized form the course plans states that the student, after having completed the course, is expected to be able to:

- Integrate knowledge acquired in previous courses by building a computer controlled device. (Section 1 of the CDIO Syllabus)
- Use a structured tool for project management extensively, including to write and follow up project and time plans and other relevant documents. (Sections 4.3-4.6)
- Take part in engineering teamwork in an industry like context, and to actively contribute to a well functioning project group (Section 3.1)
- Demonstrate various engineering skills, such as measurement technology, trouble shooting, system thinking, structured design, modern development tools etc. (E.g. Sections 1.2-1.3, 2.1-2.3)
- Communicate orally and in written text. (Section 3.2)

Standard 8 - Teaching and learning based on active experiential learning methods.

Active learning is a vast area within education, and the term normally refers to situations when the students participate in the learning process by doing something besides passive listening. The learning activities presented in connection with Standards 4 and 5 definitely belong to this category. In control, similar to many other engineering disciplines, there are many possibilities for active learning, such as laboratory exercises, homework assignments, study visits, case studies, etc. One type of learning activity that automatically leads to active learning is computer supported exercise sessions followed by computer supported examination. This has been used within the control education at Linköping University for almost two decades, and a more detailed description can be found in Gunnarsson and Millnert (1997).

Standard 9 - Actions that enhance faculty competence in personal and interpersonal skills, and product, process, and system building skills.

Standard 10 - Actions that enhance faculty competence in providing integrated learning experiences, in using active experiential learning methods, and in assessing student learning.

Standards 9 and 10 address the very important question of development of faculty competence, both in general and concerning personal and interpersonal skills, and product, process, and system building skills. The possibilities for and organization of faculty development differ a lot between universities. An important aspect is also which role qualifications and experiences within education play concerning recruitment and promotion at a particular university. In many cases, and this is also the situation for the engineering education at Linköping University, the persons and bodies managing the education programs do not have any direct influence on the competence development process for the faculty members, and this is instead determined from university and department level. This situation becomes visible when different institutions carry out the self-evaluation based on the CDIO Standard, mentioned in Section 3.4, since the ratings for Standards 9 and 10 often get relatively low values.

4.5 Assessment

Standard 11 - Assessment of student learning in personal and interpersonal skills, and product, process, and system building skills, as well as in disciplinary knowledge.

In most of the design-implent experiences within the Applied physics and electrical engineering program the tasks are carried out according to a project model of the type depicted in Figure 3. Using the project model the work is supposed to follow a structured flow, and in addition to giving structure to the work, it enables continuous assessment of the process and system building skills. This is explained in some detail in Svensson and Gunnarsson (2005).

Fig. 3. The LIPS project model. The project consists of three phases and the boundaries between the phases are determined by Tollgates 2 and 5. The figure shows the various documents that are produced during the execution of the project, and they are part of the continuous assessment.

Standard 12 - A system that evaluates programs against these twelve standards, and provides feedback to students, faculty, and other stakeholders for the purposes of continuous improvement.

From a control perspective it is obvious that a system for program evaluation, quality assurance and continuous improvement involves one or several feedback mechanisms. Measuring the quality of the result and taking actions in order make the process outcome come closer to the target is very natural. A solid background in control is important and useful in order to understand the benefits and limitations when applying a feedback mechanism in this context. One main challenge is how to define and measure quality in education, both in engineering education and in general. This is an ongoing discussion, and e.g. Sweden is in the process of introducing a new quality assurance system, which will have close connections to the European Standards and Guidelines (ESG), see ESG (2016). In particular Standard 7 talks about collection of data to be used for monitoring of quality, but it is not specified which quantities to measure. In general, quality refers to the properties of a product or a service, and it is sometimes questioned if this can be
transferred to the education context. By instead talking about the result it can be argued that the result of the education is the knowledge, skills and attitude the student brings with him/her when graduating from the university. The quality of the education is hence tightly connected to the question of how well the knowledge, skills and attitude of the graduate match the expectations and requirements of the professional career. A main challenge is then to have suitable mechanisms to measure the quality, defined in this way.

5. CONCLUSIONS

The CDIO framework for development of engineering education has been presented, including the overall ideas, the fundamental documents, and some development tools. The automatic control subject and its role in engineering education has been studied using the CDIO Standards as reference. Some examples from the engineering education at Linköping University have been presented with special focus on the control education.

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