IO (IMPLEMENT AND OPERATE) FIRST IN AN AUTOMATIC CONTROL CONTEXT

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ABSTRACT

A first course in Automatic control is presented. A main objective of the course is to put most of the emphasis on the Implement and Operate phases in the process of developing a control system for a process. The course is built around a large amount of student active learning based on three extensive laboratory exercises, where each laboratory exercise can have duration of up to two weeks. For each of the laboratory exercises there is a sequence of learning activities supporting the students' learning: Introductory lecture, problem solving session, preparation work, help-desk session, independent work in the laboratory, and a final demonstration of the control system. In addition there is a small project where the task is to write a manual for a process operator. The laboratory tasks involve implementation of a control system in an industrial PLC (Programmable Logic Controller) and development of an operator interface.

KEYWORDS

Active learning, laboratory exercise, PLC-programming, operator interface, Standards 7, 8, 11

INTRODUCTION

According to the CDIO framework, see Crawley et al (2014), the goal of engineering education is that every graduating engineer should be able to:

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

Assuming that this characterization is adopted, a logical consequence is to design engineering education with this goal in focus. Traditionally a course in an engineering discipline starts with the theoretical basis (including analysis tools), continues with design methods, where the result in many cases is an equation on paper, and sometimes ends with some type of implementation, while the operate phase seldom is covered. This paper presents a course in Automatic Control named Industriella Styrsystem, see Industriella styrsystem (2016), given at Linköping University. One aim of the course is to put emphasis on the Implement and Operate phases in the process of creating a product or a system. However, in order to make the implementation meaningful a minimum amount of theory is provided, and a pedagogical challenge is to do that with limited use of mathematics.

Designing a course where the aim is to emphasize the Implement and Operate phases implies a substantial amount of student active learning, and this is also the case in this course. The core of the execution and examination of the course consists of three big laboratory exercises and a small project. Since the execution of the different laboratory exercises overlap in time, and resources in terms of equipment are limited this puts strong requirements on the students' abilities to plan the work.

The paper is organized as follows. It starts by giving a brief introduction to the subject, and the following section gives an overview of the course and discusses the expected learning outcomes and the structure of the learning activities. The next section presents the equipment and the various software tools are presented. In the following sections the emphasis is on the contents and the execution of the course via the Conceive-Design-Implement-Operate phases. Finally the paper ends with some conclusions.

ABOUT THE SUBJECT

Automatic control is a key enabling technology in many engineering products, processes, and systems, and the task for an automatic control mechanism is to make a product, process, or system behave in a desired way. The field is sometimes called The Hidden Technology, Åström (1999), since its presence in the different applications is seldom visible. Instead the effects can be observed indirectly via the operation of the object under control. Automatic control can be found in a large number of applications, ranging from process industry, aerospace applications, passenger cars and trucks, power systems, consumer products like mobile phones and computers, biomedical engineering equipment, etc. The objectives for using automatic control mechanisms depend on the application, but they involve aspects like quality, productivity, safety, efficient use of energy and other resources, comfort, etc. One of the fascinating features of the subject is that the creation of a real world control systems includes several disciplines, including mathematical models and tools, process knowledge, hardware and software technology, sensor and measurement technology, etc. 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.

The subject is often seen as core engineering knowledge, and it is part of the curriculum in many engineering education programs around the world. Hence there are a lot of textbooks available in the subject, like e.g. Dorf and Bishop (2008) and Franklin et al (2010) in English and Glad and Ljung (2006) in Swedish. Many of the textbooks have similar structure, starting with some examples, continuing with the mathematical background, and then spend most of the presentation on various analysis and design methods. To less extent implementation aspects are given attention in these books. So in a sense, this represents the conventional way to present the subject in the engineering education. A pedagogical challenge in automatic control education is to connect the world of mathematical models, i.e. differential equations and Laplace transforms, with the real physical world. A first step is often to use simulation in order to support the understanding and intuition, and to help the students to connect e.g. time and frequency domain properties, and a second step is to carry out experiments using physical processes. Despite the fact that experiments using real hardware plays an important role there is a trend, for economic reasons, to use more and more of virtual and remote equipment. See e.g. Dominguez et al (2014) and de la Torre et al (2015).

ABOUT THE COURSE

Basic facts

The course is given for the Bachelor of Science program in Mechanical Engineering (Swe: Högskoleingenjörsprogrammet i Maskinteknik) during the second half of the spring semester of year one. The course comprises 6 ECTS credits, and there are normally around 65 participants in the course. The main part of the learning activities is based on three large laboratory exercises and one small project. The third laboratory exercise uses different hardware and software, and a somewhat different control problem is studied. This laboratory exercise will hence be left outside this paper. In addition there are four lectures and four exercise sessions supporting the preparations of the laboratory exercises. The project is tightly connected to the first two laboratory exercises, and the task is to write an operator manual for the control system. The laboratory exercises rely on a substantial amount of independent work by the students, and the duration for each laboratory exercise can be up to two weeks. More details about the organization will be given below.

The required knowledge and skills from previous courses in the curriculum include first order differential equations and integrals from the calculus course, basic skills in programming, basic knowledge about binary numbers, together with skills in writing reports. What is also of fundamental importance, even though not so visible in the curriculum, is the ability to work independently, take initiatives, and to use a systematic approach for trouble shooting.

Another consequence of the character of the course, with three large laboratory exercises, is that it also requires a substantial amount of planning by the students. Problems with completing the laboratory tasks or the project and finishing the course in time can often be connected to insufficient planning. It should also be noted that the students follow two other courses in parallel, where one of them also comprises laboratory exercises.

Learning outcomes – short summary

The learning outcomes of the first two laboratory exercises and the project can be summarized briefly as follows:

- Implement the relationships

$$I_k = I_{k-1} + K\frac{T_I}{T_S}e_k$$
$$u_k = K\,e_k + I_k$$

(i.e. a discrete time version of a so called PI-controller) in an industrial PLC (Programmable Logic Controller). Implementing the relationships above may look deceptively simple, but, as will be described below, it includes numerous practical aspects related to the hardware and programming environment.

- Determine the coefficients K, T_I and T_S such that the algorithm is able to control the behavior of a laboratory scale process.
- Develop an operator interface that presents relevant information to a process operator and allows the operator to modify the operation of the plant.
- Write a manual for the operator describing the process, the control system, and a method to tune the coefficients of the control algorithm.

Remark: As mentioned above, the third laboratory exercise deals with sequential control, which is a particular class of control problems. The structure of the learning activities is similar to the other two laboratory exercises, but since the equipment (a model factory producing Lego cars) and software are different this exercise is left outside the presentation.

Learning outcomes with reference to the CDIO Syllabus

The CDIO Syllabus offers a structured way to specify expected learning outcomes, see The CDIO Syllabus (2016), and in this section we will discuss the expected learning outcomes of this course using the CDIO Syllabus as reference.

1. **Disciplinary knowledge and reasoning:** The learning outcomes of the course are clearly connected to section 1.2 Core engineering fundamental knowledge, with some basic understanding of system models and feedback control, but with emphasis on implementation aspects of control systems.
2. **Personal and professional skills and attributes**: Due to the nature of the subject and the organization of the learning activities with extensive independent work, the learning outcomes are mainly connected to sections 2.3 System thinking and 2.4 Attitudes, thought, and learning respectively. System thinking, in terms of subsystems and interaction between them, is fundamental within the subject. Among the several relevant subsections in 2.4 one can mention 2.4.2 Perseverance, urgency and will to deliver and 2.4.7 Time and resource management respectively.
3. **Interpersonal skills: Teamwork and communication:** The entire examination of the course is based on the laboratory exercises and the project. The learning activities are carried out in pairs, and this means that the course will give thorough practice in teamwork in a small team, connected to section 3.1 Teamwork. The purpose of the project is to write a short manual intended for an operator with limited knowledge in the automatic control subject. The report is supposed to give an overview of the process and the control system, a description of the user interface, and some guidelines for tuning of the control system. This task is hence related to section 3.2 Communications.
4. **Conceiving, designing, implementing, and operating systems in the enterprise, societal, and environmental context – The innovation process**: As indicated already by the title of the paper the emphasis of the course is in the implement and operator phases, and hence the learning outcomes have closest connections to sections 4.5 Implementing and 4.6 Operating of the CDIO Syllabus.

Structure of learning activities

Given the desired learning outcomes as described above, it is natural that the course will have a big emphasis on student active learning. It would be very difficult to practice implementation in real hardware without a substantial amount of active learning.

For each laboratory exercise the overall structure of the learning activities is as follows:
- Introductory lecture presenting background material.
- Problem solving session dealing with problems related to the laboratory tasks.
- Independent work with preparation tasks. Access to a reasonable amount of assistance upon request.
- Helpdesk-sessions, where the students are expected to present their solutions to the preparation tasks.
- An initial, scheduled, and supervised session in the laboratory.

- Independent work in the laboratory. Since the number of workplaces is limited the student groups have to make reservations in advance to get access to the workplaces.
- During the laboratory work there is access to a reasonable amount of assistance upon request.
- Demonstration of the working solution to the supervisor.

The project is connected to the first two laboratory exercises, and the execution of the project task, i.e. tuning of the control system and writing of a manual for an operator can start as soon as the first laboratory exercise has been completed.

EQUIPMENT AND SOFTWARE TOOLS

Industrial process control systems typically involve a large and complex industrial process and a substantial amount of control equipment. Real industrial processes are very seldom available for education purposes, and instead one has to use affordable and safe laboratory scale equipment. Figure 1 shows the type of equipment that is used in this course, and it consists of the following hardware and software components:
- A process consisting of two water tanks on top of each other, a pump, and sensors measuring the water levels in the tanks.
- An industrial PLC of the type Siemens SLC5/03.
- A standard PC to be used as operator station.
- The software tool RSLogix in which the program to be executed in the PLC is developed.
- The software package InTouch and, in particular, the tool WindowMaker, which is used to develop the operator interface.

Figure 1: Laboratory scale plant and operator workplace.

Both for the PLC program and the operator interface the student groups are given a program skeleton to start from in the development process.

CONCEIVE PHASE

The Conceive phase in a development project deals with the problem of identifying needs of e.g. economic, environmental, or quality character, and where the introduction of a new product or system can contribute to fulfilling the needs. For the automatic control subject there are many examples both in industrial processes and in consumer products where the automatic control functionality is crucial for the operation. In e.g. a paper mill there are hundreds of control systems contributing to the task of maintaining the quality of the product, efficient use of energy and raw material, and keeping the emission of waste products at a minimum. In practice this means controlling physical quantities like level, temperature, pressure, flow, concentration, etc.

DESIGN PHASE

The aim in this phase is that the students should be able to carry out a simple model based design of a control algorithm, via the use of so called lambda-tuning. A main pedagogical challenge is to present a sufficient but minimal amount of "theory" in order to make the laboratory experiments meaningful. This includes:
- Introducing the *process* concept.
- Introducing *inputs*, *outputs* and *disturbances*.
- Motivating that a constant input value eventually results in a constant output value, (i.e. the *static* behavior), and that another constant input value results in another constant output value.
- Motivating that a sudden change of the input value, from one constant value to another, will lead to a gradual change of the output from a constant value until it reaches the constant value corresponding to the new input value (i.e. the *dynamic* behavior).
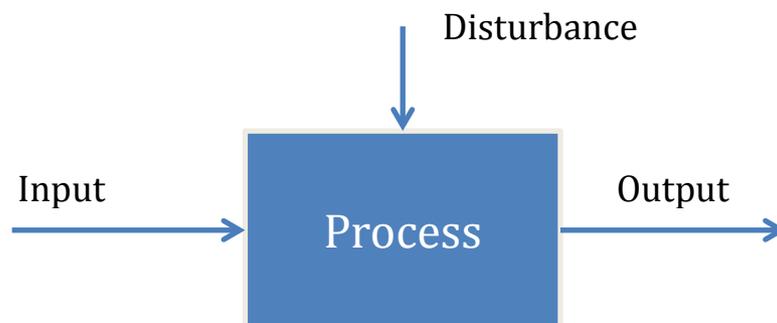

Figure 2: Block diagram description of the process to be controlled.

In e.g. an indoor climate control application the output represents the indoor temperature in a building, the input is the applied heating power, and the disturbance is the outdoor temperature.

- Introduction of the two parameters, *time constant* and *static gain* respectively, which describe the properties of the change of the output value relative to the change of the input value. The parameters are illustrated in Figure 2.
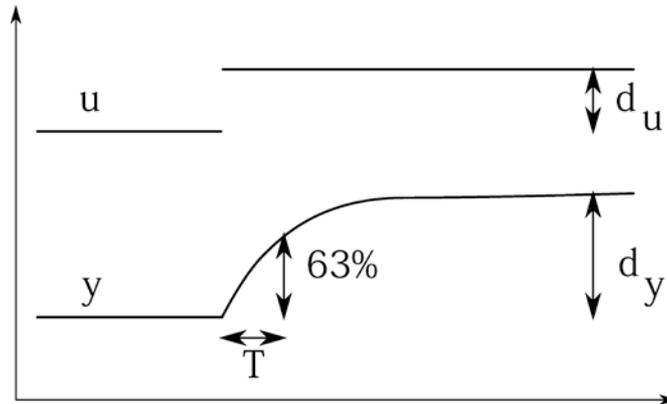
Figure 3: Change of output value y as result of change in the input u. The input change is denoted d_u, and the resulting change of the output is denoted d_y. The static gain is obtained as the ratio $k = d_y/d_u$, and the time constant T is obtained as the elapsed time from the change of the input until the output has reached 63 % of the final value.

For the climate control example Figure 3 says that a constant level of input power gives (after some time) a constant indoor temperature and that, after a sudden increase of the power level the temperature will gradually change and finally settle on a higher constant temperature.

- Introduction of the *feedback principle* where the input is determined as a function of the observed output.
- The properties of *proportional* and *integrating feedback*.
- A simple *design rule,* so called lambda tuning, to determine the gains of the proportional and integrating feedback as functions of the time constant and static gain.
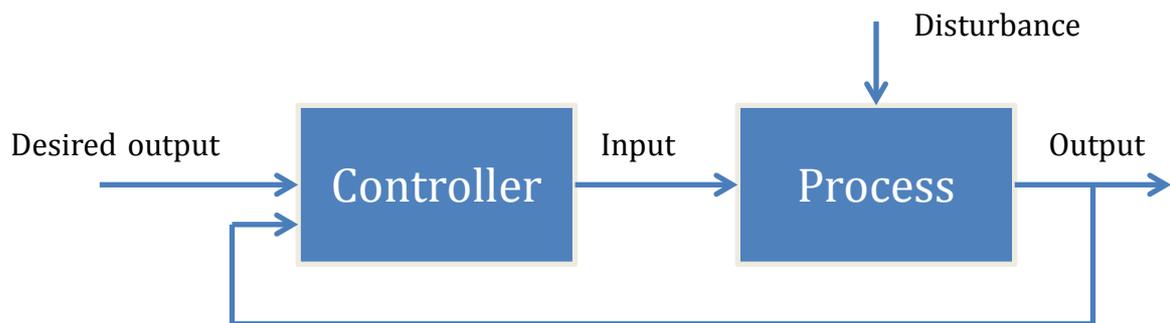

Figure 4: Block diagram description of the feedback control system.

In the climate control example Figure 4 means that the controller, typically a computer program, at every time instant compares the present temperature to the desired temperature and, depending on the outcome of this comparison determines a suitable input power. The outcome of the design phase is hence a mathematical description of how to determine the input power as function of the desired and present temperature.

IMPLEMENT PHASE

Recall the equations above, i.e.

$$I_k = I_{k-1} + K\frac{T_I}{T_S}e_k \quad (1)$$
$$u_k = K\,e_k + I_k \quad\quad (2)$$

The task is to implement equations (1) and (2) in an industrial PLC in order to control a laboratory process. At the first sight it may seem very simple, but since it is will be done using real industrial hardware and is meant to cover relevant practical aspects the task involves a number of issues:
- The program is developed on a PC using a development tool called RSLogix, and then downloaded and executed on the PLC.
- The programming is done using so called ladder diagrams where conditions, e.g. comparisons and logical checks, and actions, e.g. multiplications and logical operations, are represented by graphical blocks.

In the first laboratory exercises the students start from a given program skeleton with a built-in PI-controller, and add the following extra functionalities to the control system:
- Ability of the program to change between manual and automatic control of the tank level.
- Ability to choose which tank level to control.
- A supervision function that detects if there is risk for overflow in any of the tanks and then automatically switches to manual control and sets the input signal to zero.

In the second laboratory exercise the task for the students is to implement the PI-controller from scratch, i.e. to replace the PI-controller used in the first exercise. This implies several new practical aspects to take care of:
- The PLC uses integer arithmetic, and parameters and values are represented using 16 bits, including one bit for the sign. This implies that the programming has to be done with care in order not to cause numerical overflow in e.g. multiplications. One remedy is to use suitable scaling of all variables and parameters in order to find a trade-off between accuracy and risk of numerical overflow. The scaling makes it necessary to keep the scaling of each individual variable in mind, so that various operations are done using the correct scaling. Another remedy is to utilize the built-in check that detects if an overflow has occurred in a multiplication. In such a case one of the factors is rescaled and the multiplication is carried out again.
- The execution of (1) and (2) can under some circumstances result in a value of the input signal that exceeds the physical limits. Hence, the equations have to be complemented with a check and truncation of the input signal in order to avoid this.
- A straightforward implementation of (2) in combination with truncation of the input signal can deteriorate the performance of the control system via a phenomenon called integrator windup. In order to handle this problem (2) has to be modified using some suitable method.
- For accuracy reasons the integrating feedback has to be updated using a lower frequency compared to the proportional feedback. This is achieved by using a timer block in the PLC program.
- The performance of the PI-controller implemented from scratch should also be compared with the built-in controller.

OPERATE PHASE

The parts of the course that can be connected to the Operate phase involve the development of an operator interface and the creation of an operator's manual. The design of operator interfaces is an entire discipline in itself, and the aim is to provide initial insight into some of the aspects that need to be considered when designing an operator interface. The development of the operator interface is also done in steps distributed over the two laboratory exercises.

The interface is required to comprise the following features:
- Display of the levels of both tanks, both graphically and via numerical values.
- An alarm that turns on a red light when any of the two levels exceeds 80 % of the maximum level.
- A mechanism that turns off the pump, and hence the flow into the tanks, when either of the levels exceeds 90 % of the maximum level.
- Switches that enable change between manual and automatic control, and between the built-in controller and the controller developed by the students.
- Sliders, buttons and text fields that enable tuning of the coefficients of the PI-controller.
- Graphs showing the current value and time history of actual and reference tank levels and pump speed.

An important part of the course, related to the Operate phase, is the project where the task is to write a manual for an operator. The manual is expected to present the following aspects:
- A brief description of the entire system, including the tank process, the PLC, the PC, and an explanation of which information that is exchanged between the different units.
- A thorough presentation of the interface.
- A brief description of the parts of a PI-controller and the features of the different components.
- A description of one tuning method for selecting the coefficients in the PI-controller.
- In addition, the manual should meet the general requirements for a report of sufficient quality.

The project has to be completed and the manual has to be handed in within two weeks after the completion of the first laboratory exercise.

ASSESSMENT

In a previous session the intended learning outcomes of the course were listed with reference to the CDIO Syllabus, and the aim in this section is to summarize how the learning outcomes are assessed. The assessment is based on two main components:
- Demonstrations of working solutions that fulfill the list of requirements on functionality and user interface
- The operator manual.

Below it will be discussed how these two activities are connected to the assessment of the learning outcomes.

1. **Disciplinary knowledge and reasoning:** The disciplinary knowledge is shown by first being able to implement and tune a PI-regulator, and second by describing for a user, in the operator manual, the function of the different parts of the regulator and how to tune them

2. **Personal and professional skills and attributes**: The learning outcomes concerning System thinking, section 2.3, are assessed via the creation and operation of the control system, where the hardware and software component are integrated. The overall system and the interactions between the components are also explained in the operator manual. The various learning outcomes connected to 2.4, Attitudes, are assessed by showing the ability to finish the tasks given the different deadlines. As mentioned, the execution of the different laboratory exercises, and at the same time managing two other courses in parallel, put strong requirements on the ability to plan the activities. This includes e.g. attending the helpdesk sessions before the first scheduled laboratory session, getting the solution of the first laboratory exercise approved before the second laboratory exercise can be started. The writing of the manual can start after the first laboratory session has been completed, and the first version should be delivered within a specified time limit. A limited time for revision is allowed before the final deadline for the manual.

3. **Interpersonal skills: Teamwork and communication:** The teamwork is assessed indirectly via the ability of the two group members to solve the task together within the given time limits. Furthermore, it is required that both students in the group are able to explain how the solution works. The learning outcomes connected to 3.2, Communication, are assessed via the operator manual. This year a new component will be introduced, where the students are supposed to go through and sign a checklist which will be handed in together with the first version of the report. By signing the checklist the students certify that they have checked the most basic requirements concerning a report, like figure and table captions, reference handling, spell checking, etc. Normally only one revision of the operator manual is allowed.

4. **Conceiving, designing, implementing, and operating systems in the enterprise, societal, and environmental context – The innovation process**: The key point of the paper is the emphasis on the implement, section 2.5, and operate, section 2.6, phases of the engineering process. Being able to develop a control system, including the operator interface, that fulfills the requirements concerning functionalities using real industrial hardware is seen as the evidence that the learning outcomes have been reached.

DISCUSSION

The course has been given for approximately five years and seems to have found a suitable form concerning learning objectives, organization and execution. The following observations can be made:

- The organization and execution of a course of this kind require that the involved teaching staff pays sufficient attention on the planning and timing of the various learning activities.
- Similarly, the course requires careful planning by the students in order to fit the various learning activities into the schedule together with other courses.
- The helpdesk sessions are very important in order to ensure that the students are sufficiently prepared before the laboratory exercises.
- The students find it positive that the main part of the learning activities is based on practical work in the laboratory.
- The writing of the operator manual gives good training in written communication.
- The instructions, e.g. in terms of a check-list, concerning the writing process can be improved.

CONCLUSIONS

A first course in Automatic Control has been presented, where one of the aims of the course is to put emphasis on the Implement and Operate phases in the creation of a new product or system. Another aim is that the students should work with real industrial hardware and get insight into the practical aspects of the implementation. The learning activities are based on three large laboratory exercises and one project. In addition to giving disciplinary knowledge in the subject, the course gives opportunities to develop several engineering skills, e.g. teamwork, communication, system thinking, planning of time and resources, etc.

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