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Teaching Control Principles to Industry Practitioners

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ABSTRACT
This paper addresses the need of continued education of process industry practitioners such as operators and instrumentation engineers. The process industry regulatory control tuning situation of today is reviewed. Areas of potential improvement are identified. Especially, useful laboratory experiments are outlined, forming the curriculum for a practically oriented course. The suggested course was given within PICLU – a regional collaboration between academia and process industry in Scandinavia. The experience from the course is discussed and it is concluded that the course format provides an efficient way to increase on-site performance in process industry.

Keywords
Automatic control education, continued education, laboratory

1. INTRODUCTION
Automatic control is a subject rich in both mathematics and practical considerations. To device adequately working control systems, it is therefore important to have a broad competence span. Teaching automatic control to an audience without a strong mathematical background can be challenging, for students and instructors alike. Even the more basic theory of the commonly occurring Proportional Integrating and Derivating (PID) controller is based on concepts of ordinary differential equations, linearization, Laplace transforms and matrix algebra [1].

Likewise, an audience without practical experience generally has difficulties estimating the skills and effort required to implement a control system in a non-ideal world [2].

Part of the activity of PICLU, the Process Industrial Centre at Lund University [3], is to provide technology transfer to regional process industry. As part of this mission, the Department of Automatic Control at Lund University is giving a series of courses aimed at different categories of industry professionals. The first course in this series was held in the spring of 2010 and aimed at practitioners such as instrumentation and process engineers.

The main purpose of this paper is to draw attention to a situation,

where much is to be earned. In addition, it is the hope of the authors to inspire to take similar pedagogic initiatives and reach out to audiences, which are generally forgotten, mainly due to lacking mathematical background. For this purpose a course format, which was found to work well for instructors and participants alike, is presented.

2. AUDIENCE
The audience consisted of industrial professionals, working in close connection to process industry processes. An illustrative way of introducing the background of the audience is through the functional model of Skogestad, [4], shown in Figure 1.
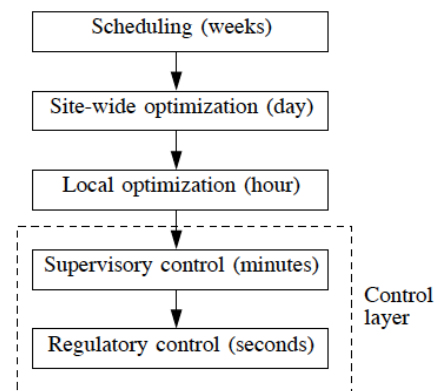

Figure 1. Skogestad's functional model of a process industry facility.

In his model, Skogestad decomposed a generic process industrial plant into a vertical functional hierarchy. Each level is defined through its complexity and time scale of operation. The mentioned audience is employed within what Skogestad refers to as the 'Control layer', decomposed into 'Supervisory' and 'Regulatory' control. Practically this means that they work in close connection to physical processes, and have extensive hand-on experience.

Parts of the audience have an academic background, however, not often in control systems. Some have started their careers as process operators and transcended from working in the 'Regulatory control' layer, to a more conceptually focused position.

Unlike what is commonly found among students in academia, the audience has a strong practical background and good practical intuition. They are generally motivated to learn new concepts, directly applicable in their professional work. However, they are not used to the format of university education (lectures, exercises,

laboratory sessions) and have a limited theoretical background in control systems.

One aim of the course would hence be to exploit the intuition and motivation of the participants, without being limited by the format in which control systems are traditionally taught at an introductory university level. Before formulating the goals of such a course in greater detail, motivations for giving it will be presented.

3. THE IMPORTANCE OF CONTINUED EDUCATION

3.1 The Tuning Situation

PID control [1] is a technology well over 50 years old. Still, today, over 95 % of all regulatory control loops in process industry are PID. Of the PID loops over 90 % are PI. Studies, e.g. [5], have shown that adding derivative action would increase performance in many cases. However, it has often been omitted due to difficulties of tuning.

Although more advanced control strategies such as MPC [6] are emerging to some extent, the base level controllers in an MPC solution are still typically PIDs.

As with any control technology, the PID controller needs to be tuned to function adequately. Even though most industrial PIDs are compensating stable, slow, reasonably damped processes with mainly monotonous step responses [7], several surveys witness of surprisingly poor performance. A survey by Ender in 1993 [8] on regulatory PIDs concludes that:

- > 30 % operate in manual
- > 30 % increase short term variability
- ≈ 25 % use factory default parameters

A similar survey by Bialkowski in 2002 gave the following numbers for PID controllers within process industry:

- 50 % work well
- 25 % ineffective
- 25 % dysfunctional

A plausible reason for these figures is the cost of properly modeling and tuning a PID control loop. Hiring a consultant for the task is USD $250-1000$ in work costs alone, according to a survey by Honeywell [9]. Many companies have this competence in-house, but the holders of it are generally occupied above the 'Control layer' of Figure 1.

Providing operators and instrumentation engineers with the knowledge needed to conduct model-, rather than intuition-based tuning could contribute to improve the situation significantly.

3.2 Reliance, Disuse and Misuse

Handling undesired behavior in process industry control loops often involves switching the loop to manual mode. If the control system is critically malfunctioning, this is well motivated. However, switching to manual mode when the control is functional or not switching when it is dysfunctional should be avoided.

In [10], the concepts of misuse and disuse are defined in the context of control reliance. Disuse is the under-utilization of functional control, while misuse occurs when the operator overly relies on control. Psychological experiments in the cited paper show that disuse and misuse decreases significantly if the operator is given a rational explanation to the behavior of the control system. The main conclusions in the paper is that optimizing a plant alone, is of limited value, if the operators are not updated on the underlying principles. The *interaction* between automated aid and human operator must be considered.

3.3 Increased Efficiency Through Awareness

Another reason for continued education is to develop the ability to identify 'low hanging fruit'. Some control systems can be significantly improved by retuning or introducing an extension such as derivative action, a feed forward link or cascade structure. By learning to identify these situations, an individual can contribute significantly to the increased efficiency of the control system.

3.4 Personal Motivation

There is an additional motivation for continued education, which differs slightly from the ones already mentioned. The individual employee participating in the education, will generally feel recognized by his/her company. This fact, in combination with the aspects discussed above, may contribute to a more positive atmosphere, where own initiatives for improvements are closer at hand.

4. COURSE LAYOUT

4.1 Goals

A challenge in automatic control education is how to include practical experiments in an otherwise mathematically oriented curriculum [11]. The challenge faced here is the opposite. Practitioners generally have many hours of on-site experience. Rather than providing a complete control course, the proposed course aimed at fulfilling the following goals:

- Give a thorough understanding of the simple control loop.
- Become familiar with process types common in industry.
- Recap manual tuning of the PID controller and introduce alternatives.
- Go through the anatomy of the PID controller and handle practical implementation aspects.
- Introduce more advanced control structures such as cascades and feed forward links.
- Discuss the influence of sensor and actuator placement and characteristics.

Based on these goals, and motivated by experience from teaching undergraduate control courses, a course outline was assembled.

4.2 Methodology

The design of the course was influenced by the concepts of 'zone of proximal development' [12] and 'deep versus superficial learning' [13] by Vygotsky and Säljö, respectively. A brief review

of these pedagogical ideas, and their influence on the course, are given below. Similar concepts are thoroughly handled in [14].

4.2.1 Zone of Proximal Development

The ability to acquire new knowledge and skills is strongly coupled to what one presently knows. Vygotsky studied this basic idea more closely and introduced the 'zone of proximal development', being a set of yet unacquired knowledge or skills, lying close to what is already familiar to the learner. Based on Vygotsky's studies, it was natural to make laboratory exercises a central part of the course, since the participants were themselves practically oriented. Furthermore, effort was spent to identify topics of significance, which were both within the zone of proximal development of the audience and of practical use in their professional lives.

4.2.2 Deep Versus Superficial Learning

Säljö makes a clear distinction between deep and superficial learning. Deep learning is more persistent and more easily extendable. However, it requires more of the learning process. Exemplifications, learning by solving problems and learning by teaching each other are known methods to achieve a depth of learning. Lectures and text books are rich in information and provide good referencing material, while they risk to result in more superficial learning. To address this, the course was given a practical problem focus. In the interest of time, some material was presented by means of traditional lectures.

4.3 Structure

In order to relate to the practical background of the audience, all teaching was strongly coupled to laboratory exercises. One-hour lectures were followed by hands-on sessions in the lab, where the theoretical results were applied to a physical plant. There was also a course book, [7], covering the material on a conceptual level. The book was not used extensively during the course itself, but was given to the participants to keep for future reference. In addition to taking notes, participants were strongly encouraged to print plots of experimental result, which was possible to do in an uncomplicated way due to support in the lab user interface.

5. THE LABORATORY EQUIPMENT

In this section, the laboratory process is introduced. A physical overview of the process is followed by a presentation of its dynamics. Finally, the choice of the particular process for the course is given.

5.1 Process Overview

The equipment chosen for the course was a cascaded double tank. The process was developed at the Department of Automatic Control, Lund University, and is used regularly in the basic undergraduate, nonlinear, predictive and process control courses. An earlier version of the process is described in [15]. An operational sketch of the process is shown in Figure 2.
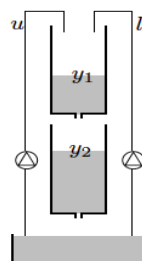

Figure 2. : Operational sketch of double tank process.

Figures 3(a) and 3(b) show a CAD drawing and photograph of the physical process. Note that only the leftmost half, indicated by dashed lines in the photo, was used.
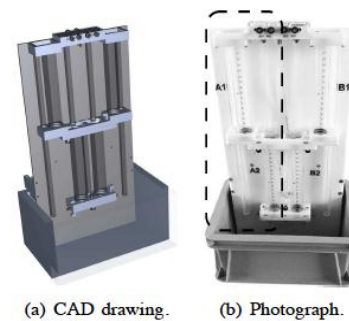

(a) CAD drawing. (b) Photograph.

Figure 3. CAD drawing and photograph of laboratory process. The region corresponding to Figure 2 is marked by dashed line in photograph.

5.2 Dynamics

5.2.1 Open Loop Dynamics

Deriving the nonlinear tank dynamics based on [16] and linearizing them around a stationary point is part of the introductory undergraduate control course at Lund University, giving a good connection between theory and practice. The nonlinear dynamics are given below for completeness:

$$\frac{dy_1}{dt} = \frac{a_1}{A_1}\sqrt{2gbh_1} + \frac{a}{A_1}q(u+l)$$

$$\frac{dy_2}{dt} = \frac{a_1}{A_1}\sqrt{2gbh_1} - \frac{a_2}{A_2}\sqrt{2gby_2}$$

where u is the input flow and l an input disturbance. The water level of the upper tank is y_1, while y_2 is the level of the lower tank. A_k are the tank cross sections and a_k are the cross sections of the holes connecting the tanks. The acceleration of gravity is denoted g while α and β are unit conversion constants. Finally, θ is the Heaviside step function, manifesting that the tanks cannot be emptied by means of the pumps.

5.2.2 Actuator Linearization

Two cheap centrifugal bilge pumps actuate the input u and 'load disturbance' l, respectively. The system input u is the pump voltage, while the input of the model (1) is the flow q. The pump dynamics from u to q are approximated well by the square root function, with stochastic deviations caused by mode jumps. For pedagogical reasons it was decided to hide this nonlinearity by closing a flow PI loop over each pump and a corresponding upstream Venturi flow sensor, as shown in Figure 4.
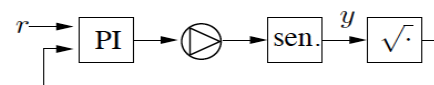

Figure 4. Flow control loop. ('sen' denotes 'sensor'.)

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As shown in Figure 5, the nonlinear voltage to flow characteristics were replaced by linear flow reference to flow ones. The PI loop of Figure 4 was tuned a magnitude faster than the open loop tank dynamics, hiding its dynamical behavior.
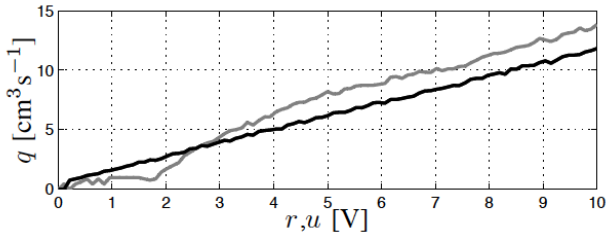

Figure 5. Open and closed loop pump characteristics. Flow q is plotted against pump voltage u (gray) and PI reference r (black).

5.3 Interface

The process has an on-board micro controller, handling sensor A/D conversions, actuator D/A conversions, execution of the pump linearization control loop and serial port communication with a PC.

Using serial port (or USB to serial) enables the process to be used with all major operating systems.

The PC side interface can be implemented in various ways. A Java interface with graphical windows similar to those in a process industry control room is used in the basic course and shown in Figure 6.
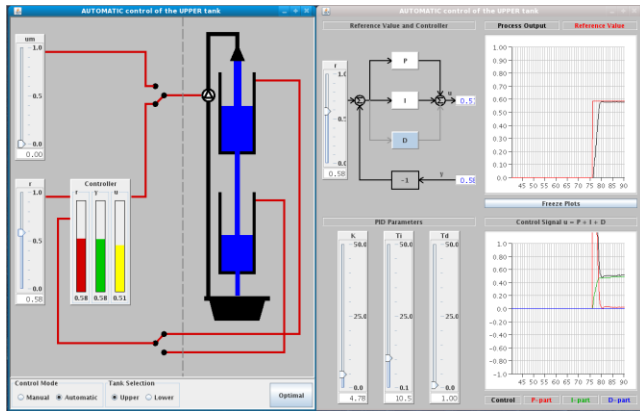

Figure 6. Java GUI used in the basic undergraduate control course.

Other courses facilitate a Matlab/Simulink interface through locally developed communication blocks. Real time simulation is enabled by the TrueTime real time kernel [17].

The main advantage of using a tailored high level interface, such as the Java one, lies in its flexibility in terms of graphical user interface (GUI). On the other hand, it is less transparent and hence structural changes may require substantial efforts.

While the Simulink model is not as flexible in terms of GUI, it is straight forward to introduce structural changes. Also, Matlab scripts can be used to set parameters, run simulations and plot data. These features are frequently exploited by students in advanced undergraduate courses at the department.

For the particular course, the GUI was implemented in Simulink. An effort was made to abstract away all technical detail and only present what was necessary to illustrate a given concept. Each experiment was associated with a tailored model, which was opened simply by writing the model name at the Matlab prompt. One of these interfaces are shown in Figure 7.
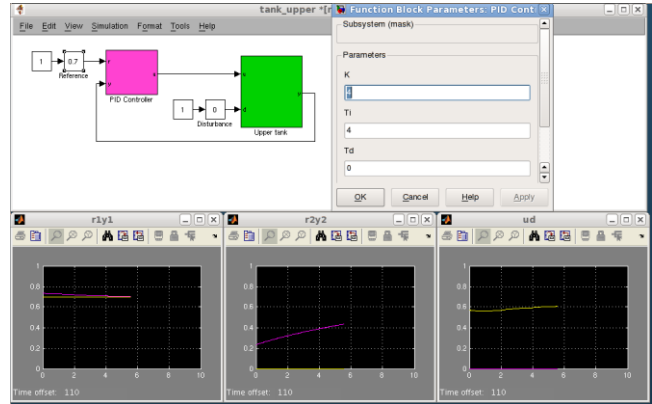

Figure 7. Simulink GUI. (The PID parameter window is opened by double-clicking on the PID block.)

Experiments could be started or stopped at any time. By typing a simple command a paper printout, as the one shown in Figure 8, could be obtained.
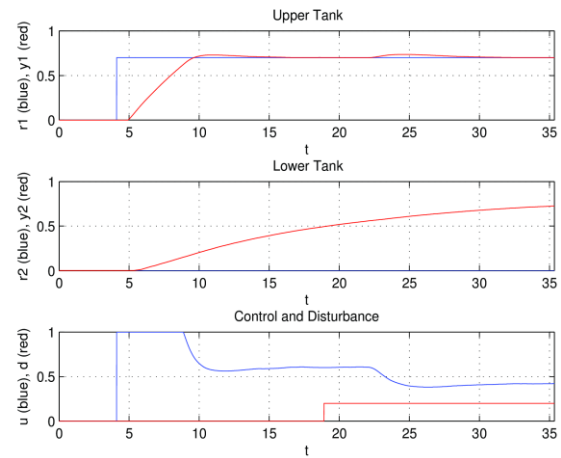
Figure 8. Comprehensive printout of signals from the latest experiment.

5.4 Motivation of Process Choice

The process was chosen due to several facts, in coherence with guidelines from [18], [19] and [20]. Appealing features include:

- Intuitive, but not trivial, dynamics

- Suitable time scales

- Visual and audible feedback

- Easy to generate load disturbances and measurement noise

- Relevant in process industry (buffer tank)

The dynamics enable the demonstration of concepts such as model based controller tuning, disturbance feed forward, cascaded control and gain scheduling.

In the undergraduate curriculum additional features of the process are explored in greater detail:

- Nonlinear dynamics
- Asymmetric actuation
- Sampled system (zero order hold AD/DA, anti aliasing, etc.)
- Embedded micro controller and real time communications
- Easily extendable to Multi Input Multi Output (MIMO), using all four tanks of the process
- Model uncertainties in terms of structure and parameters

These features can be bought to attention also during a course for industry practitioners. However, they are not as essential for the practitioner as the topics of the experiments, presented in the following section.

6. SUGGESTED EXPERIMENTS

Below follows a brief description, together with objective and learning outcome, of a set of experiments. Each experiment demonstrates a concept, significant for the process industry practitioner. Together they form the laboratory part of the suggested course.

6.1 Intuition Based Tuning

The first laboratory session was devoted to getting familiar with the process by means of self-designed open loop experiments. In addition, participants were asked to design controllers for the levels in the upper and lower tank, respectively.

The objective was to get the participants familiar with the equipment and dynamics, rather than producing a well tuned loop. Before moving on, the participants should have gained an intuitive understanding that a two-capacitive process is harder to control than a single capacitance. They will have experienced the need of systematic tuning methods, when process dynamics are slow. Those not having a recent experience with PID tuning would in addition obtain a conceptual understanding of the PID parameters and their influence on loop performance.

Experimenting with P, PI and PID controllers, the participants would see that pure P control leaves a static error, and that derivative action can increase performance when controlling the lower tank level, but not the upper. These results are all covered in the lectures. Finally, by choosing the amount of low pass filtering on the measurement signal, the influence of noise on the control signal, when using derivative action, was studied.

6.2 Model Based Tuning

Generally the participants managed to tune an acceptable PI loop for the upper tank within minutes. However, the slow dynamics of the lower tank posed a harder challenge. The process was harder to control per se, and the dominating time constant of 30 s rendered tedious experiments necessary.

Having learnt the step response method of Ziegler and Nichols [21] and a more recent alternative [1], the participants were encouraged to make step response experiments and identify parameters of a first order plus time delay model. These were obtained visually from the input–output data plots.

The objective of this exercise was to demonstrate the practical use of simple model-based tuning methods. It also provided a natural opportunity to emphasize the importance of tuning with respect to load disturbances, rather than reference tracking, since most industrial processes operate with constant reference.

Most participant found that model based tuning provides a good starting point for further manual tuning, especially if process dynamics are slow (as in the case of the lower tank).

6.3 Disturbance Feed Forward

Feed forward from a measurable disturbance to control signal, is a simple technique, which can reduce the influence of measurable load disturbances significantly. Ideally, one would use a dynamic link, based on the disturbance path model. However, in many cases, even a static link can provide significant performance improvement. In this experiment, the pump generating the signal l in Figure 2 was used to generate a step input disturbance. The participants are to choose the feed forward gain F (initially $F = 0$) in Figure 9 and investigate its influence when controlling the level of the upper tank.
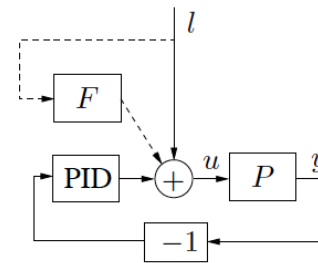

Figure 9. Block diagram of the disturbance feed forward experiment.

After having conducted this experiment, it should lie closer at hand to add feed forward sensors and compensators, where beneficial.

6.4 Cascaded Control

In this experiment, a cascade control solution, consisting of two PID loops was investigated. The setup is shown in Figure 10.
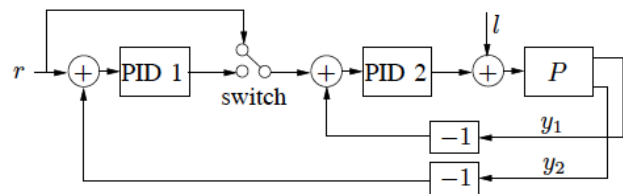

Figure 10. Block diagram of the cascaded control experiment.

Rather than controlling the lower tank level, using only y_2, a cascaded solution, using both y_1 and y_2 was used. The inner loop, closed from y_1, had a dominating time constant considerably faster than that of the outer loop. By tuning a tight inner loop (using the switch), the participants were able to treat the inner loops as a static gain, while later tuning the outer loop.

The primary objective of this exercise was to demonstrate that more advanced control structures, such as cascades, can bring performance improvements at a low cost. It also provides background for a continued discussion on sensor and actuator placement.

The participants should be able to identify when cascaded control is useful and be able to tune two cascaded PID loops, starting with the inner one. By experimenting with disturbance steps, l, the participants will find that the cascade suppressed them more efficiently than does a single loop PID solution, using only y_2.

7. OUTCOME

All along the course the instructors had discussions with the participants about the course material, both from a content perspective and from a teaching/learning perspective. This was done in order to assure that the course contained relevant material for the participants (e.g. not too hard and not too easy) and to assure that the participants appreciated the way the course was given (e.g. how much time to be spent on theory and how much time to be spent on the laboratory exercises). Relevant and possible adjustments were done during the execution of the course. At the end of the course, the participants were also asked to fill out an evaluation form with feedback to the instructors about the course. Getting feedback from the participants at the end of the course is important, not for this course itself, but because this course (as well as other courses) will be given to industry practitioners again. The four instructors involved in the course had a meeting shortly after the end of the course in which they gave their own reflections on the course and worked through the feedback from the participants.

7.1 Instructor Evaluation

The four instructors involved were satisfied with the course. Some reflections from the instructors: 'the questions asked by the audience were different from the ones we usually get from engineering students in the way that they were often more practical oriented and less theoretical', and 'The course was designed not to contain too much material, this left room for reflections – I feel the students went away with a good understanding of the material'.

7.2 Participant Evaluation

Some reflections from the participants: 'large and complex area described in an easy and understandable way', 'advance quicker in the start of the course and spend more time on the harder problems at the end', 'good atmosphere, good practical exercises', 'suitable level and useful material'. In the questionnaire the participants should formulate what they had expected of the course and how well the course matched their expectations; 94 % felt that the course matched their expectations in a good or very good way, 6 % said ok.

8. CONCLUSION

The professional role and background of the audience were presented in Section 2. Section 3 investigated the needs of further education of process industry practitioners. The goals and structure of a course aimed at providing continued education are given in Section 4. Large parts of the suggested course are based on laboratory experiments, reviewed in Sections 5 and 6. Experience from the course were given in Section 7.

It was concluded that the practically oriented curriculum of the course enabled the participants to learn within their zone of proximal development and acquire a deep, rather than superficial learning. It is the belief of the authors that the course format provides a both time-wise and economically efficient way to increase on-site performance in process industry.

9. ACKNOWLEDGMENTS

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