INCORPORATING PRACTICAL AND SYNTHESIS CONTENTS IN UNDERGRADUATE CONTROL EDUCATION

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ABSTRACT

This paper revisits the effort over the last decade in making undergraduate control education more useful and attractive to both the control engineers and the engineers at large. With the help of further coverage in new textbooks, more practical and synthesis contents in the control courses have been incorporated. Gaps still exist, particularly in the areas of PID control and auto-tuning, fuzzy control, overall control strategy, control structure and systems thinking, and these will be elaborated. A major challenge is in the coverage of more practical and synthesis contents in the introductory common control course for all engineers. How this may be resolved is discussed. Finally, the need for new teaching approaches such as the use of interesting case studies and the use of problem-based learning will be outlined.

KeyWords: Control education, practical contents, synthesis, control structuring, systems thinking.

I. INTRODUCTION

Much progress has been achieved over the last two decades in textbook publications, curriculum development, laboratory experimentation and computer aided design software to improve control engineering education [1]. Effort has also been made in addressing the challenge in incorporating practical contents in control engineering courses owing to feedback from industry that the conventional courses were too academic resulting in major adjustments needed in practice. For instance, as stated in an IFAC Control System Report Card From Industry in the mid 90s, the most important Control System topics included implementation, identification and intelligent control. With regard to “biggest disappointments”, it was clear that industry found that few fresh graduates understood industry expectations, while many fresh graduates were disappointed regarding the impact of theory.

According to recent literature [2-5], progress has indeed been made to include preparation for practice. However, most control courses and curricula are still more comprehensive in preparing graduates for an R&D career. For preparing graduates for practice, the most balanced programme is that for Chemical Engineering with excellent textbooks such as [6] and [7]. As Control has been fast developing as an “enabling technology” for many different disciplines of engineering, there is also a great demand for a common foundation course for all engineers. It will help the non-specialists to better appreciate the potential of control technology, as well as to reduce the communication gap between them and the control engineers in practice. This will further enable the full potential of control technology to be exploited in the diverse areas of household appliances, consumer electronics, automotive and aerospace systems, manufacturing systems, transportation systems, chemical and environmental systems, and even biological, economical and medical systems [3]. Such a course needs to provide coverage on basic analysis which is more heavy on mathematics, synthesis aspect which is less mathematical and the practical examples used should be cross-disciplinary. This goal is not yet widely achieved.
The purpose of this paper is to provide a review of the effort over the last decade in making undergraduate control education more useful and attractive to both the control engineers and the engineers at large. It will highlight gaps which still exist in the incorporation of practical and synthesis contents inspite of the good progress made. It will end with a discussion on implementation challenges.

II. PROGRESS IN INCORPORATING PRACTICAL CONTENTS

The need for incorporating practical contents in control engineering courses has been wellknown [1], [3], and [8]. Good progress has been achieved as evidenced by textbooks published over the last decade [9-11]. From either the list of contents, or especially revealing from the index, practical topics such as integrator anti-windup, two-degree-of-freedom (which decouples set-point and load responses), control of nonlinear gain (through simple gain-scheduling), multi-loop control (cascade, feedforward, decoupling, override, etc) and dead time compensation (Smith predictor, inferential control, etc) have been well addressed.

More progress will be needed in incorporating sequence control, PID control, auto-tuning, fuzzy control and control loops trouble-shooting. Sequence control is used in a batch control system such as a chemical reactor, or in the start-up and shut-down phases of a complex process such as a power plant. It is also common in a discrete-parts manufacturing plant. Its design involves much process knowledge and it often involves the use of a separate programmable logic control (PLC) system or software. From a feedback control perspective, it is critical to do this part well in practice as it brings the dynamic system near to the operating point so that the linear feedback regulating system may take over. The need to include the other practical topics is elaborated in the following.

PID control has only been briefly covered in many textbooks although it has become the most pervasive control technique in industry [2]. Little in-depth research into its effectiveness, its analytical design and its auto-tuning, was done in the past until the advent of relay auto-tuning in the early 80s [11-13]. Academics have since shown immense interest on this topic as shown by the rapid growth in the publications on PID research as listed in the EI Compendex [14]. For instance, the total number of publications on PID research was 59 in 1980; it jumped to 265 in 1985 and 767 in 1995. In 2000, an IFAC Workshop on Past, Present and Future of PID Control was held. It is anticipated that the new understanding and deep knowledge on PID control and its auto-tuning [15] will soon filter down to undergraduate textbooks. The extension of PID auto-tuning technique for the auto-tuning of model-based advanced control will follow subsequently.

Fuzzy control had a slow start since its invention by Zadeh in 1965 [16], but was successfully applied in industry since the 80s [17-20]. Despite its simplicity and its wide acceptance in industry, it has been resisted by many academics as it does not depend on a precise mathematical model [18]. This is not totally surprising as it is quite typical of the so called “disruptive technology” which is cheaper, simpler and easier to use [19], and initially ignored by those who embrace the conventional approach.

If we stay away from the subjective debate on whether fuzzy control is superior to conventional control, we can objectively find two definite roles of fuzzy control. One is that it is a simple means to achieve “task control” which is different from the usual “setpoint control” [18]. Many successful applications of fuzzy control in consumer electronics, robotics and manufacturing control applications are indeed for task control. A wellknown example of task control in the process industry is the “averaging” level control of surge tank. If a conventional controller is used, its tuning is made adaptive such that it is sluggish in the larger part of the working range as tight setpoint control would defeat its function in isolating disturbances between the upstream and downstream processes [21]. The other definite role is to use fuzzy control as a means to automate human tasks in supervisory control of a large, complex and nonlinear plant without much explicit knowledge of its mathematical model [20]. These two definitive roles of fuzzy control could be easily incorporated in future control courses as an intermediate topic between on-off control and precise (conventional) feedback control.

Finally, the topic of trouble-shooting control loops should be included in any basic control course. It is a fundamental education for all engineers that a control system may fail in practice. It is beyond poor controller tuning. Key factors for control failure include insufficient process analysis, improper selection of sensors, improper countermeasure to disturbance, improper control strategy and improper selection of actuators [2]. Learning from control failure also improves one’s understanding about control and makes the subject less boring.

III. GAPS IN INCORPORATING SYNTHESIS CONTENTS

Synthesis is not simply limited to controller design as may be implied in most undergraduate textbooks. It
encompasses much broader and earlier engineering decision makings such as overall control strategy, process design, control structuring and controller design. While they have been covered in more detail in some advanced textbooks and in graduate courses, their introduction ought to be brought forward in undergraduate curriculum and textbooks. This has indeed been partially achieved in an excellent textbook by Seborg et al. [6] in which the synthesis content was brought forward from Chapter 28 in the first edition to Chapter 10 in the second edition.

In the initial phase of a major control engineering project, one needs to carefully consider an appropriate overall control strategy as it has the consequence of cost, performance and risk [22]. Yet it is hardly addressed in most standard control textbooks. For instance, the use of passive control, such as a tuned mass absorber, may be sufficient for the purpose of suppressing vibrations. Passive control is simple and cost effective as the sensing and actuation functions are integrated within the subsystem, and an independent energy source is usually not needed [22]. A much tighter performance specification would call for the more sophisticated active control in which distinct sensors, actuators and controllers are needed while the underlying physics or chemistry needs to be well understood.

One would then consider the interplay between process design and control [11]. It is well known that process design affects the nature of dynamics and hence the control problem. For instance, the experience in poor control in the past might have led to the use of a surge tank to absorb process upsets, at the cost of additional equipment; the level control of the surge tank also becomes one of task control rather than set-point control. On the other hand, the demand of a faster switching-over time for variable product specifications may necessitate the elimination of the surge tank hence creating a tougher multivariable control problem. Another frequent encounter is the consideration of stability versus controllability which have contradictory requirements [11]. For instance, an aircraft design for easier manoeuvre at high speeds may become unstable at low speeds, creating a challenging control problem. Running an exothermal chemical reactor at operating conditions in which the reactor is open-loop unstable, hence harder to control, may be necessary to achieve a higher yield [11].

The next decision is the amount of effort that should be spent on the controller design. For systems that will be mass produced, such as a control system for hard disk drives, it may be appropriate to spend much engineering effort to design the controller. In many other cases such as a large chemical plant with a few hundred control loops, however, it is not economically feasible to spend much effort on individual controller designs. For such applications in process control, it is common to use a standard general-purpose controller with adjustable parameters. Off-line or on-line controller tuning and re-tuning methods may then be applied to determine the optimal values of the adjustable parameters.

Finally, one needs to choose a suitable controller depending on the control problem at hand and the performance specification given. While PID control is very effective and hence widely used in industry, there are situations when PID control is not very effective. When to apply or when not to apply PID control is not well explained in undergraduate textbooks. Similarly, information on when to apply advanced control, and what the appropriate advanced controller such as pole-placement or Smith predictor, etc. should be selected for the specific process dynamics and desired performance are generally not well covered in undergraduate textbooks and courses. The achievable performance also depends on the available measurement, actuator range/resolution, the noise environment and the accuracy of the dynamic model available.

In many real problems which are large and poorly defined in the initial phase, a “control structuring” step is necessary before one could apply control system design which can deal with a small, well-defined problem [6,7,11]. Unfortunately, structuring cannot yet be put into and taught as a complete systematic framework. While based on scientific principles, it often requires creativity and ingenuity like a craft. As in the field of computer science, a combination of “top-down” and “bottom-up” approaches is used in industry, often by “structuring masters” who then mentor their younger successors. Inspite of this situation, some basic principles of structure [11] could be introduced in undergraduate courses.

A top-down approach will require first the selection of control principles, followed by choice of control variables, measured variables, and pairing of these variables. A control principle gives a broad indication of how a process should be controlled. A good choice of control principle can often simplify the control problem. Its selection also involves technical and economical trade-offs. Figure 1 shows the control of a drum boiler, with three possible control modes and hence also different pairings of control and measured variables [11]. In the boiler follow mode, the generator speed is controlled directly by feedback to the turbine valve, achieving rapid control of generator speed and power output, at the expense of thermal strains on the turbine and the boiler. In the turbine follow mode, the steam
pressure is kept constant and hence the thermal stresses are much smaller; the turbine speed control is however more sluggish. The sliding pressure control mode is a compromise between the boiler follow and turbine follow modes. Other examples can be found in [6,7,11].

In the bottom-up approach, a choice of control variables and measurements would come first. Different control structures are then introduced until a satisfactory closed-loop system is obtained. The control structures used are standard types based on the ideas of feedback, feedforward, cascade, selector, inferential control, etc. [6,7,11]. The use of several measurements to manipulate one control variable is an important feature seldom discussed in introductory textbooks. For instance, in the compressor control system of Fig. 2, three measurements through a selector controller and a cascade controller are used to control the motor speed [7]. Through the combinations of different control structures, very complicated control systems can be built up.

Finally, it is often taken for granted that engineering students already understand systems thinking (system dynamics and control strategies) or could easily learn it by themselves or in practice. Hence the control course contents would focus on stability, performance, etc. using mathematical tools. Insufficient attention is paid to the control ‘physics’ aspects such as the critical role of feedback, the effect of dead time, nonlinearity, etc. on control performance; and how one should deal with them [3]. In fact, basic knowledge on systems thinking has parallel applications in other fields such as business management. And without the assumption that students already understand this topic, systems thinking has been given much more thorough and explicit coverage in business management courses. For instance, the following simple management example illustrates the application of systems thinking to introduce a feedback control at the right place [23]. A company’s new invention created enormous market demand; more investments were provided and sales continued to grow; three years later, the demand suddenly fell and the company went bankrupt. Applying systems thinking, it was found that the rapid growth of demand was not matched by production capacity hence causing a backlog and poor delivery time; eventually the customers switched to a competitor’s product. The solution as shown in Fig. 3 is simply to place a feedback loop on delivery time and regulate the production capacity accordingly. Perhaps such basic systems thinking could be introduced in a first course in control for engineers through the use of such common-sense case studies of management or engineering problems!

IV. IMPLEMENTATION CHALLENGES

The incorporation of practical and synthesis contents in undergraduate control courses is not too difficult in the case for students who specialize and hence attend several advanced modules in Control Engineering. The most challenging problem is in incorporating these types of content in the common foundation course for all engineers. The available textbooks either do not cover them, or cover them too late and hence are often skipped in the pressure of time. One possible solution is to adopt a mixed sequence of analysis and synthesis as outlined in a possible course content in Fig. 4. It will ensure that sufficient exposure is provided to some practical and synthesis contents (indicated in [6]) which will benefit all engineers, irrespective of whether they move on to other specialization or to further their education in Control Engineering. It would be feasible also to create room for these contents by eliminating or reducing the treatment of some outdated or less important classical approaches. For instance, with modern CAD packages, there is little need to spend too much time on the manual method of plotting root loci. The laborious graphical methods for designing lead-lag compensators can nowadays be replaced quickly by an analytical de-
Finally, there is an urgent need to introduce new teaching approaches. The use of interesting case studies and patent documents, involving the participation of industrial specialists where available, will be particularly suited for the practical and synthesis contents, and will also make the undergraduate control courses less boring. Hopefully it will help to attract more bright students to opt for control specialization subsequently. Another approach is to use the so called “Problem-Based Learning (PBL)”.

V. CONCLUDING REMARKS

Much progress has been made in incorporating practical and synthesis contents in undergraduate control education. Some practical topics such as sequence control, PID control, fuzzy control and control loops trouble-shooting could be introduced or given more depth if they have already been briefly introduced. Gaps in incorporating synthesis contents, such as overall control strategy, control structuring and systems thinking, would need urgent attention. Furthermore, two major challenges need to be addressed in future. One is the design of a more interesting common foundation course in control engineering for all engineers which has appropriate practical and synthesis contents. The other is in introducing new teaching approaches such as case studies and problem-based learning. Action will be needed as awareness of these challenges has generally been achieved.

REFERENCES


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