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Teaching Digital Controllers for Finite Settling Time by Using Model-based Control Education (MBCE) in a Constructivist Framework

Adrian Gambier*

*Automation Laboratory, University of Heidelberg, 68131 Mannheim, Germany
(Tel: +49 621 1812783; e-mail:agambier@ieee.org)

Abstract: In this contribution, a new approach for teaching digital controllers for finite settling time and deadbeat response is proposed. Essential concepts of deadbeat control are revised and shorted in order to simplify the teaching. The approach is base on a constructivist instructional model, which is supported by well-known pedagogical tools as the *learning cycle*, the *sandwich structure* and the *portfolio assessment*. Finally, the lecture is designed in details and CACSD tools are introduced by mean of an illustrative example.

1. INTRODUCTION

In Murray et al. (2003), it is recommended that the control knowledge base should be unified and compacted by integrating material and frameworks. On the other hand, it was pointed out in Albertos et al. (2006) that it is difficult to find teaching material that integrates computer aided control design tools (CACSD) into the subject. Hence, it is possible to infer that the control community wishes in a near future to have available compact material, which integrates CACSD tools.

However, this aim cannot satisfactory be reached if founded pedagogical methods are not adapted for the field and consequently applied. The theoretical basis for implementing this kind of teaching is the *Constructivism* (see for example Ertmer and Newby (1993) for details), which was first developed by Bruner (1960) on the cognitivist ideas of Piaget. The constructivist theoretical framework assumes that "*learners construct new ideas or concepts based upon their current/past knowledge*". Under the constructivist framework, several instructional models have been proposed (see Beaudin (1995) for a review). In Gambier (2006), a new instructional model for teaching lectures is proposed and applied in the area of control engineering.

In the current paper, the model of Gambier (2006) is complemented and applied to organize a lecture about the design of digital controllers with finite settling time as well as deadbeat response. The contribution of the current work can be addressed in three different directions: *i*) it can be viewed as an example of application the instructional model to the control engineering field; *ii*) a new presentation of a well-known topic as the deadbeat controller design, and *iii*) an example about how to introduce Matlab/Simulink programmatically into the lecture.

The paper is organized as follows: after the present introduction, the instructional model for designing the lecture is presented in Section 2. In Section 3, concepts of the subject, which has to be taught, are described and analysed. Moreover, a simulation example is used to illustrate the studied theme. Section 4 is devoted to design the lecture about digital controllers with finite settling time by using the idea of model-based control education. Finally, conclusions are drawn in Section 5.

2. MODEL-BASED CONTROL EDUCATION (MBCE)

The instructional model used to organize lectures was already presented and funded in Gambier (2006). Therefore and for sake of completeness, the approach will shortly be presented in the rest of this Section.

The general concept is shown in Fig. 1. It is based on the combination of three pedagogical tools: the *learning cycle* of Karplus (1974), a modified *sandwich structure* (Gerbig and Gerbig-Calcagni, 1998) and a *learning portfolio* (Barton and Collings, 1997). Thus, the model contains an ordered structure, it is founded in a recognised instructional model for science and it includes a modern evaluation system. These components are explained in details in the following.

2.1 Learning Cycle

The learning cycle was first proposed by Karplus for teaching physics. It was later introduced into the biology by Lawson et al. (1989) and into the chemical engineering by Wankat and Oreovicz (1993) as the "*scientific learning cycle*". It consists of three phases (see left side of Fig. 1):

1. *Exploration*: students learn through their own actions and advance with minimal guidance. The learners are expected to raise questions that they cannot answer with their present ideas or reasoning patterns. This phase can be done individually or in groups.
2. *Concept introduction*: the professor introduces terms, definitions and equations that are necessary to fill in the missing information from the exploration phase.
3. *Concept application*: in the third phase, students apply the concept to new situations and examples.

2.2 Sandwich Structure

The "*sandwich structure*" (Gerbig and Gerbig-Calcagni., 1998) consists in structuring the lecture according to the scheme given in Fig. 1 (centre). In this scheme, four different phases can be distinguished: the *introducing* and *concluding phases*, the *collective information intake phase* (collective learning phase) and the *active information-processing phase* (individual learning phase).

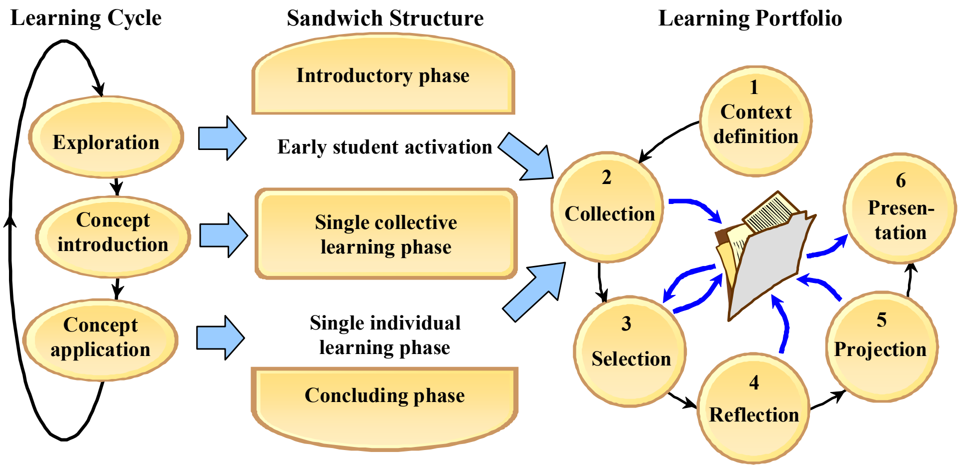

Fig. 1. Instructional model to design active learning lectures (Gambier, 2006)

1. *Introductory phase*: In this phase, the teacher introduces the subject and the *learning objectives*. It is a good idea to present here an *Advance Organize* (Ausubel, 1960), i.e. a picture, diagram or scheme that summarizes the complete lesson including concepts and their relationships in a schematic form. An *eye catcher* like an opportune cartoon can also be introduced at the end of this phase, when the teacher is moving to the next one.
2. *Early activation of students*: After the introductory phase, it is important to plan a short phase of individual learning whose objective is to motivate the students. Typical activities for this phase are, for example, partner interview about the contents of the last class, writing down the feeling about what suggest the title of the new lesson or an exercise to associate new words with old concept using structure building techniques or a semantic network. This phase should be short (between three and seven minutes).
3. *Collective Learning Phase*: After the early activation of students, collective learning and individual learning phases takes alternatively place. The collective learning phase is normally used by the teacher to introduce new information in the form of a lecture or presentation. This phase should not be longer than 20 or 25 minutes in order to avoid attention distraction.
4. *Individual learning phase*: During the individual learning phase, students are committed to work individually, in pairs or in very small groups in order to solve an exercise related to the presented topic. In this phase, discussions, readings, problem-solving activities can be used. The time dedicated to this phase varies depending on the time for the complete lesson and the number of alternations that are planned. A typical number is 10 until 25 minutes. The exercises planned for this phase may have different degrees of difficulty in order to take into account individual students' skills.
5. *Concluding phase*: This phase is transfer oriented. It is important here to remark the most important points of this lesson, which are necessary to reach the learning objectives (presented at the begin). The subject of the next lecture may also be described in this phase. Finally, a short feedback about the current lesson can be asked to the students. Notice, that the feedback concerning the deep understanding is obtained from the individual learning phase, where the students have to apply the new introduced concepts.

2.3 *Learning Portfolio*

A *Learning Portfolio* is a representative or selective personal collection of information describing and documenting a person's achievements and learning. It can be designed to assess student progress, effort, and/or achievement, and encourage students to reflect on their learning. A portfolio becomes a *portfolio assessment* when (1) the assessment purpose is defined and (2) criteria or methods are made clear for determining what is put into the portfolio, by whom and when; and (3) criteria for assessing either the collection or individual pieces of work, which are identified and used to make judgments about performance (Barton and Collings, 1997).

The development of a portfolio (electronic or paper) consists of six stages (Fig. 1, right side): *Context definition*, *collection*, *selection*, *reflection*, *projection* and *presentation*. The context definition set the framework in which the portfolio will be developed including e.g. conditions for the assessment. In the *collection* stage, students have to save *artefacts* that are the evidence about learning successes and fulfilment of requisites to pass the course. During the *selection,* students review and evaluate the *artefacts* that they have saved, and identify those that demonstrate achievement of specific objectives. The *reflection* helps the students to evaluate their own growth over time and their learning achievement. Students compare in the *projection* stage their reflections to the standards and performance indicators, and set learning goals for the future. Finally, students share their portfolios with their peers in the *presentation* stage.

A learning portfolio provides direct evidence of the quality of a student's work and a basis for evaluation of work-in-progress. It defines assessment as a process rather than necessarily as "*final*". Furthermore, it permits a re-evaluation by alternative evaluators, at different times and in different contexts (different from providing final quantitative grades). Finally, it empowers the student to self-assess and continuously expand or otherwise improve her/his work. Techniques for portfolio assessment can be found in Barton and Collings (1997).

This model is applied in the following to a lecture of a digital control course, whose subject is presented in the next Section.

3. THE SUBJECT TO BE TAUGHT

Controllers that yield a closed-loop system with finite settling time as well as deadbeat response are a particular characteristic of discrete-time systems. This kind of control systems has no counterpart in the area of linear continuous-time systems. Therefore, it is a very attractive subject and it is practically included in all textbooks on digital control. Such controllers are derived in the literature by following different ways. In Isermann (1989), the subject is presented as a special case of cancellation controllers and imposing conditions for the input and output after n sampling periods, where n is the system order. Ogata (1994) takes advantage of FIR systems (Finite Impulse Response) and used the cancellation controller, as well. Åström and Wittenmark (1997) presented the problem as a case of pole placement for the state-space representation.

For this lecture, the controller will be derived by using a FIR system but cancellation controllers and pole placement will not be explicitly utilized. Thus, it is not necessary to have previously introduced these controllers.

3.1 Problem Formulation

The control design problem can be formulated as follows: For the digital control system shown in Fig. 2, where the plant is described by the pulse transfer function in z domain

$$\frac{y(z)}{u(z)} = G(z) = \frac{B(z)}{A(z)} \tag{1}$$

with coprime polynomials

$$B(z) = b_0 z^m + \cdots + b_m \ \text{ and } A(z) = z^n + \cdots + a_n, \quad \text{for } n \geq m, \tag{2}$$

a controller

$$\frac{u(z)}{e(z)} = G_c(z) = \frac{Q(z)}{P(z)} \tag{3}$$

with e, Q and P given by $e(z) = r(z) - y(z)$,

$$Q(z) = q_0 z^\nu + \cdots + q_\nu \ \text{ and } P(z) = z^\eta + \cdots + p_\eta, \quad \text{for } \eta \geq \nu, \tag{4}$$

should be designed, such that the close-loop control system will show a finite settling time with zero steady-state error in response to a step set point.

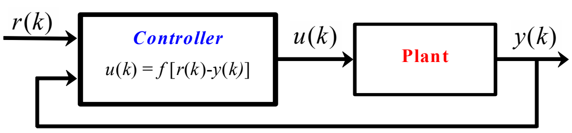

Fig. 2. Digital control system

3.2 Systems with FIR Response

In order to solve the problem, the concept of FIR systems is required. The dynamic of a FIR system is given by the transfer function

$$\frac{y(z)}{u(z)} = \frac{F(z)}{z^N} = \frac{f_0 z^N + f_1 z^{N-1} + \cdots + f_N}{z^N} \tag{5}$$

and its most important characteristic is that the output reaches the steady-state value after N sampling periods.

3.3 Controller Design

From the characteristic of FIR systems mentioned before, one infers that it is sufficient to require that the controller has to yield a closed-loop system that exhibits FIR dynamic in order to obtain the finite settling time, i.e.

$$G_{cl}(z) = \frac{y(z)}{r(z)} = \frac{B(z)Q(z)}{A(z)P(z) + B(z)Q(z)} \triangleq \frac{F(z)}{z^N} \tag{6}$$

and this leads to the Diophantine equation

$$A(z)P(z) + B(z)Q(z) = z^N, \tag{7}$$

whose solution produces the coefficients for Q and P. The degrees of nominator and denominator polynomials are

$$\deg(BQ) = m + \nu \ \text{ and } \deg(AP + BQ) = \max(n + \eta, m + \nu). \tag{8}$$

Since $\eta \geq \nu$ and $n \geq m$, it follows $\deg(AP + BQ) = n + \eta$.

3.4 Condition for zero steady-state error

The condition for steady-state error can be obtained for step set point by applying the final value theorem for the z transform to

$$y(z) = \frac{B(z)Q(z)\, r(z)}{A(z)P(z) + B(z)Q(z)} = \frac{B(z)Q(z)}{A(z)P(z) + B(z)Q(z)} \frac{r_0}{1 - z^{-1}} \tag{9}$$

and setting the condition $\lim_{k\to\infty} y(k) = r_0$, i.e.

$$\lim_{k\to\infty} y(k) = \lim_{z\to 1} \frac{B(z)Q(z)\, r_0}{A(z)P(z) + B(z)Q(z)} = r_0. \tag{10}$$

This lead to the condition given by

$$\frac{B(1)Q(1)}{A(1)P(1) + B(1)Q(1)} = 1. \tag{11}$$

This equality is obtained for $A(1)P(1) = 0$. If the type of the system is greater than zero, then the equality is always satisfied and no condition is required for $P(1)$. Otherwise, it is necessary to satisfy $P(1) = 0$. This condition can also be expressed as

$$1 + \sum_{i=1}^{\eta} p_i = [1\ \ 1 \cdots 1][p_1 \cdots p_\eta]^{\mathrm{T}} + 1 = 0. \tag{12}$$

3.5 Solution of the Diophantine Equation

Equation (7) including the condition (12) (if it is necessary) can also be expressed as a system of linear equations given by

$$\begin{array}{r} z^{n+\eta-1}: \\ z^{n+\eta-2}: \\ z^{n+\eta-3}: \\ \\ \vdots\ : \\ \\ z^1\ \ \\ z^0: \\ \hline P(1)=0: \end{array}
\underbrace{\left[\begin{array}{cccc|cccc} 1 & 0 & \cdots & 0 & b_0 & 0 & \cdots & 0 \\ a_1 & 1 & \cdots & 0 & b_1 & b_0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ a_n & a_{n-1} & \cdots & 1 & b_n & b_{n-1} & \cdots & b_0 \\ 0 & a_n & \cdots & a_1 & 0 & b_n & \cdots & b_1 \\ 0 & 0 & \cdots & a_2 & 0 & 0 & \ddots & b_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & a_n & 0 & 0 & \cdots & b_n \\ \hline 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{array}\right]}_{\mathbf{S}}
\underbrace{\begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_\eta \\ q_0 \\ q_1 \\ \vdots \\ q_\nu \end{bmatrix}}_{\boldsymbol{\theta}}
=
\underbrace{\left[\begin{array}{c} -a_1 \\ -a_2 \\ \vdots \\ -a_n \\ 0 \\ 0 \\ \vdots \\ 0 \\ \hline -1 \end{array}\right]}_{\boldsymbol{\alpha}} \tag{13}$$

such that the coefficients of P and Q are obtained from

$$\boldsymbol{\theta} = \mathbf{S}^{-1}\boldsymbol{\alpha}. \tag{14}$$

The Sylvester matrix $\mathbf{S}$ is invertible if polynomials $A(z)$ and $B(z)$ are coprime and the degree of polynomial $Q(z)$ is n. The last condition is given by the fact that $\mathbf{S}$ has to be a square matrix. This condition is obtained by requiring that the number of equations ($n+\eta$ from the coefficient comparison given by (7) plus condition (12) if it is necessary) is equal to the number of variables (ν+1 coefficients of $Q(z)$ plus η coefficients of $P(z)$). Hence, the condition is

$$\nu+\eta+1 = n+\eta+1 \Rightarrow \nu = n \tag{15}$$

or $\nu = n - 1$, if (12) is not included. Since $\eta \geq \nu$, it follows that $\deg(AP + BQ) = n + \eta \geq 2n$. Thus, this approach leads to a closed-loop system of with a minimum order equal to $2n$.

3.6 Obtaining Deadbeat Response

The order $2n$ can be reduced, when $P(z)$ and $Q(z)$ are chosen in such a way that $A(z)P(z)$ and $B(z)Q(z)$ have a common factor, i.e.

$$A(z)P(z) = M(z)P^{\circ}(z) \text{ and } B(z)Q(z) = M(z)Q^{\circ}(z). \tag{16}$$

In this case, the transfer function of the closed-loop system will be

$$G_{cl}(z) = \frac{B(z)Q(z)}{A(z)P(z)+B(z)Q(z)} = \frac{Q^{\circ}(z)}{P^{\circ}(z)+Q^{\circ}(z)}. \tag{17}$$

In general, this decomposition is not trivial and sometimes it is also not possible. However, a simple case is obtained when the polynomials are chosen as

$$M(z) = A(z); \quad Q^{\circ}(z) = \gamma B(z); \quad P^{\circ}(z) = z^N - Q^{\circ}(z) \tag{18}$$

Hence, the transfer function of the closed-loop system is given by

$$G_{cl}(z) = \frac{Q^{\circ}(z)}{P^{\circ}(z)+Q^{\circ}(z)} = \frac{\gamma B(z)}{z^N - \gamma B(z) + \gamma B(z)} = \frac{\gamma B(z)}{z^N}. \tag{19}$$

Consequently, the set point is reached in N sampling steps. The steady-state error will be zero for

$$\gamma = 1/B(1) = 1/\sum_{i=0}^{m}[b_i]. \tag{20}$$

Finally, the controller's transfer function is given by

$$G_c(z) = \frac{Q(z)}{P(z)} = \frac{\gamma A(z)}{z^N - \gamma B(z)} \tag{21}$$

Since degree of $A(z) = n$ and the controller has to be physically realizable, it is necessary to set $N \geq n$. Thus, the minimum degree for the denominator is $N = n$ and then the order of the closed-loop system is in this case n instead of $2n$. The obtained controller is called *deadbeat controller* because the closed loop control system with this controller has a deadbeat response to a step set point. The deadbeat response is characterized by the minimum possible setting time (n sampling instants when the control signal is unbounded), no steady-state error and no ripples between sampling periods. The controller (21) with $N = n$ is the same as the controller derived in Isermann (1989) but here it has been obtained by using a more simple procedure.

The maximum amplitude for $u(0)$ is now obtained by applying the initial value theorem of the z-transform to the function

$$u(z) = \frac{\gamma A(z)}{z^n} w(z) = \gamma A(z^{-1}) w(z) \tag{22}$$

for $w(z) = w_0/(1-z^{-1})$, i.e.

$$u(0) = \lim_{z\to\infty} u(z) = \lim_{z\to\infty} \gamma A(z^{-1}) w_0 = \gamma w_0 = \frac{w_0}{b_0 + \cdots + b_m}. \tag{23}$$

Since the coefficients b_i increase with the sampling time, the amplitude of $u(0)$ increases when the sampling time decreases. Therefore, a deadbeat response is obtained when the control signal is unbounded and the sampling time becomes a very important design parameter.

It is important to remark here that equations (7) and (21) represent the pole placement method and the cancellation controller, respectively. However, it was not necessary to introduce explicitly these approaches. Finally, notice that the controller cancels the denominator of the plant. This will be a problem if the plant is unstable. Therefore, the method is limited to stable plants. For unstable plants, it is possible to develop a deadbeat controller but the settling time will require more than n sampling periods. This is subject of another lecture.

3.7 Simulation Experiment

In order to illustrate the properties of the presented controllers, a Simulink model for the three-tank system of Fig. 3 is used.

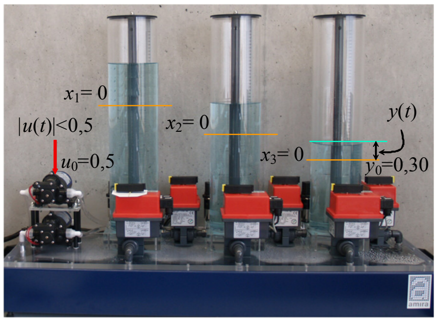

Fig. 3. Experimental set-up used in the laboratory

The plant is described by the linearized pulse transfer function

$$G(z) = \frac{0.37z^2 + 0.092z + 4.4\ 10^{-5}}{z^3 - 0.635z^2 + 0.002z - 4.6\ 10^{-10}}.$$

The controllers are obtained by using Matlab as

$$G_c(z) = \frac{3.82z^3 - 1.64z^2 + 0.005z + 1.2\ 10^{-9}}{z^3 - 0.76z^2 - 0.24z - 1.1\ 10^{-4}}$$

for the controller with finite settling time and

$$G_c(z) = \frac{2.18z^3 - 1.38z^2 + 0.004z - 9.9\ 10^{-10}}{z^3 - 0.8z^2 - 0.2z - 9.7\ 10^{-5}}$$

for the deadbeat controller. The corresponding closed-loop transfer functions are

$$G_{cl}(z) = \frac{1.4z^5 - 0.25z^4 - 0.15z^3 + 3.6\ 10^{-4}z^2 + 2.1\ 10^{-7}z + 5.2\ 10^{-14}}{z^6} \text{ and}$$

$$G_{cl}(z) = \frac{0.8z^2 + 0.2z + 9.6\ 10^{-5}}{z^3}, \text{ respectively.}$$

By using Simulink, both closed-loop systems can be simulated and compared with a digital PID controller. Simulation results are presented in Fig. 4. Fig. 4 (a) shows the simulation results for the linear control loop. After this experiment, the linearized model of the plant was replaced by the nonlinear model and all controllers were tested under this new situation. As it is possible to see in Fig. 4 (c), controllers, which have to respond in a minimum settling time, cannot satisfy the requirement when the plant is nonlinear.

The subject described in the last section will now be used to fill the structure portrayed in Section 2 in order to present an example about how to design a constructivist oriented lecture, where CACSD tools and laboratory exercises are integrated into the lecture in the form of an active learning scheme.

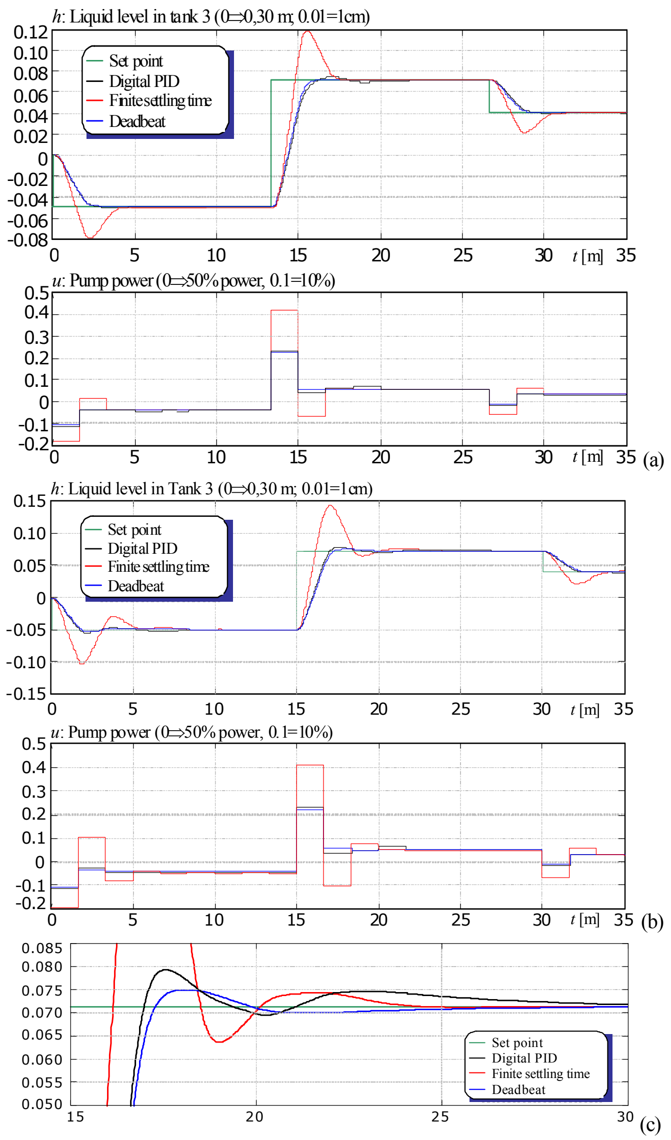

Fig. 4. Simulation results: a) linear closed-loop system, b) non-linear control system and c) zoom of Figure (b).

4. PLANNING THE LECTURE

In the following, prerequisites for understanding the lecture, a detailed description of the sandwich structure and the data for the learning portfolio are presented.

4.1 Assumed prerequisites

Because this lecture is planned into the framework of a second control engineering course, all prerequisites for this course are also valid for this lecture, i.e. it is assumed that students are familiar with the material of a basic control course. It is also understood that students are able to use Matlab/Simulink and that they attended some previous lectures on sampling, z-transform, modelling of discrete-time systems and discrete-time PID control.

4.2 Sandwich structure

Introductory phase

The introductory phase should not take more than 10 minutes. The must important topics of this phase are the *learning objectives*, the *advance organizer* and an *agenda*.

Learning objectives

At the end of this lecture, it is expected that students should be able to

- design a controller with finite settling time as well as deadbeat response
- describe controller properties, advantages and drawbacks
- simulate the control system by using Matlab /Simulink, and to
- select at least two *artifacts* for the learning portfolio.

Advance Organizer (AO)

The AO schematically describes the contents and the structure of this lecture. It is show in Fig. 5. The lecture is symbolized by a trip by bus. The bus transports the students so that at the end of the trip they should have reached the learning objectives (goal). The road has the form of a deadbeat response and the bus stops mean the different topics, which will be treated during the trip.

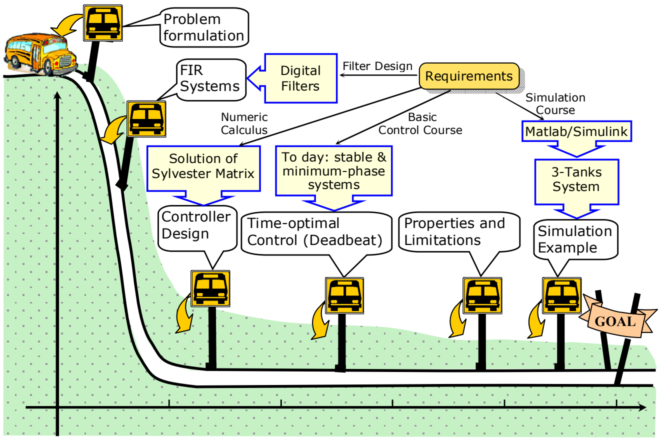

Fig. 5. Advance Organizer for the example

Agenda

Finally, the agenda for a lecture of 90 minutes can be presented to the students:

Table 1. Agenda presented to the students of this lecture

Time	Activity	Duration
x	Introduction	10´
x+10	Exercise (simple)	15´
x+25	Theoretic presentation about the controller design	25´
x+50	Exercise (complex)	30´
x+80	Summary and Conclusions	10´
x+90	End	
x: is the time at which the lecture starts		

Sandwich structure: Early student activation

According to the model proposed in Section 3. The early student activation phase has to be designed to obtain the exploration phase of the learning cycle. Thus, students should use old knowledge to gain new one. In order to reach this teaching objective, the following exercise is proposed to the students:

Obtain the closed-loop transfer function for plant model given by $G(z) = B(z)/A(z)$ and a controller $G_c(z) = Q(z)/P(z)$. Moreover, conditions to obtain zero steady-state error should be found.

Expected results: it is expected that the students obtain the closed-loop transfer function (6) but not the condition (12).

Sandwich structure: Collective learning phase

Students will not be able to continue developing the exercise proposed in the last section. Remember that they have started only using previous knowledge and this does not include deadbeat control. Hence, according to the "*concept introduction phase*" of the cycle learning it is time to introduce formal definitions and the associated mathematics. A presentation of 25 minutes is foreseen for this purpose. The teaching material has been shortly presented in Section 3.

It is important to remark now that the presentation of the material can be undertaken from two different points of view: (1) using an *inductive approach* or (2) using a *deductive approach*. Induction is the natural human learning style and therefore it is recommended as teaching style (Felder at al, 2000). However, deduction is the most used human teaching style, at least for technical subjects at university level. Thus, induction will be used in this lecture to avoid this mismatch.

Sandwich structure: Individual learning phase

It is useful to initiate this phase with a "reading as active learning" exercise (Mckeachie & Svinicki, 2006). The text prepared for the reading in this lecture is a short tutorial about the dynamic properties of the plant used for the exercise, the corresponding Simulink block diagram and some important function like *linmod*. After the reading, students should visit the computer room and start solving the main exercise, i.e. to design a controller with a finite settling time and a deadbeat controller, to implement a Simulink block diagram for the closed-loop system with the linearized as well as the nonlinear model and the designed controllers. They can use previous exercises to simulate the plant with a digital PID controller in order to obtain comparison results.

Sandwich structure: Concluding phase

At this phase, it is important to provide general remarks and a summary of the current lecture. It should be mentioned that deadbeat controllers should not be used for unstable plants. Plants with transport delays as well as non-minimum phase behaviour require a particular approach. Finally, it is also important to remark that minimum settling time cannot be reached if the input is bounded. Finally, the next lecture may be introduced.

4.3 Collecting artefacts

From the early student activation phase, students should put in their portfolios the derivation of the final equation and from the individual learning phase the block diagram for Simulink. A pair simulation curves from the computer exercise should be added. Finally, a short reflection about the properties of deadbeat control should complete the portfolio documentation.

Notice that the portfolio assessment is a long-time evaluation procedure that takes place along the course. At each lecture, only the collection stage is carried out and the portfolio assessment occurs at the end of the course and not at the end of each lecture.

5. CONCLUSIONS

In this contribution, the design of digital controllers is presented in a constructivist framework. The lecture is designed by using a new instructional model, which is based on three important pedagogical instruments, namely the sandwich structure, the learning cycle and portfolio assessment. Therefore, it is named "*model-based control education*" (MBCE). The application to a control-engineering lecture was illustrated in a digital control course, where concepts of controllers with finite settling time have to be taught. CACSD tools are naturally introduced in the design and integrated in the lecture.

This instructional model is satisfactorily being used in different courses like, digital control and physical modelling of dynamic systems. A feedback evaluation instrument is been designed for collecting data from the student.

REFERENCES

Albertos, P., D. Atherton, S. Dormido, B. Foss, A. Leva, B. Pasik-Duncan, C. Schmid, (2006). Rethinking control education in the modern world. Discussion panel organised by the IFAC TC on Control Education, and the IEEE – CSS Technical Committee on Education, 7th IFAC Symposium on Advances in Control Education, 23-24 June 2006, Madrid, Spain.

Åström, K. and B. Wittenmark (1997). Computer controlled systems. Prentice Hall, Information and System Sciences Series, Upper Saddle River, New Jersey.

Ausubel, D. P. (1960). The use of advance organizers in the learning and retention of meaningful verbal material. *Journal of Educational Psychology*, **51**, 267-272.

Barton, J., and A. Collins, (Eds.). (1997). Portfolio assessment: A handbook for educators. Menlo Park, CA: Addison-Wesley.

Beaudin, B. P., D. (1995) Quick. Experiential Learning: Theoretical Underpinnings. *High Plains Intermountain, Center for Agricultural Health and Safety* (HI-CAHS), Report No. ETT-95-02.

Bruner, J. (1960). The process of education. Cambridge, Mass: Harvard University Press.

Ertmer, P.A. and T. J. Newby. (1993). Behaviorism, Cognitivism, Constructivism: Comparing critical features from an instructional design perspective. *Performance Improvement Quarterly*, **6**, 50-72.

Felder, R., D. R. Woods, J. E. Stice and A. Rugarcia. (2000). The future of engineering education. II. Teaching methods that work. *Chemical Engineering Education*, 34, 26-39.

Isermann, R. (1989). Digital control systems. Vol. 1. Springer, New York.

Gambier, A., (2006). A new approach to design control engineering lectures: an example for hybrid systems. Proc. of the 7th IFAC Symposium on Advances in Control Education 2006, Paper No. ThD02.6, 23-24 June 2006, Madrid, Spain.

Gerbig, Chr., I. Gerbig-Calcagni, (1998). Modern didactic for computer aided education. (In German). BELTZ. Weiterbildung.

Karplus, R., (1975). The learning cycle. In F. Collea, et al., *Workshop on physics teaching and the development of reasoning*. Stonybrook, NY: American Association of Physics.

Lawson, A. E., M. R. Abraham, and J. W. Renner, (1989). A theory of instruction: Using the learning cycle to teach science concepts and thinking skills. *NARST Monograph*, No. I.

McKeachie, W. J. and M. Svinicki, (2006). McKeachie's Teaching Tips. Houghton Mifflin, Boston.

Murray, R. M., K. J. Åström, S. P. Boyd, R. W. Brockett and G. Stein. (2003). Future directions in control in an information-rich world. *IEEE Control Systems Magazine*, **23**, 20-33.

Ogata, K. (1994). Discrete-time control systems. Prentice Hall, Englewood Cliff, New Yersey.

Wankat, P. and F. Oreovicz, (1993). Teaching engineering. New York, McGraw-Hill.