Innovative Methods of Teaching the Basic Control Course

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1 Introduction

System view, understanding systems and how they are controlled, is an important discipline in engineering education. Systems are all around us. Basic knowledge about them is important for everybody. Engineers need deep knowledge enabling analysis and design of control systems. Nowadays considering the ever-increasing knowledge, the explosion of information, the available visual technics and software tools, and the emerging requirement for online distance education, there is a need to revisit the content and the teaching methodology of the basic control course.

The basic control course held for software engineering students at the Budapest University of Technology and Economics in the spring semester 2019 covered the topics of analysis and design of continuous and discrete control systems. The content of the course and the teaching methods were overviewed to respond to the challenges of the new teaching environment. A new aspect in the content of the course is the introduction of the YOULA parameterized controller design, which is a very effective method. Other controller algorithms can be considered as special cases of YOULA parameterization.

Considering the teaching method, we tried to explain the main disciplines in an understandable way to everybody and then discuss the precise mathematical description. The developed multilevel e-book, SYSBOOK, also supported the

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understanding and provided some philosophical background to the different topics. Active learning deepens knowledge. Some interactive demonstrations presented during the lectures contributed to the joy of understanding. Active participation of the students was ensured by problem-solving at the end of the lectures and by the computer laboratory exercises using software MATLAB/SIMULINK. As Open Content Development, the students can contribute to the teaching material by elaborating their own case studies about a system and its control.

2 Content of the Basic Control Course

The course discusses analysis and design of both continuous and discrete linear control systems. Nowadays discrete control systems gain increasing importance in computer control of industrial processes. Control of linear, deterministic systems is discussed. To control a system, the model of the system should be first analyzed. Real systems are generally nonlinear, which can be handled individually. For analysis of linear systems, there are general methods. Therefore it is expedient to linearize the systems in a given environment of a working point and apply control methods using the linearized models of the systems. Input/output models and also state space models are used to describe the systems. The control system should ensure the required prescribed performance of the plant. The controller is designed considering the model of the plant and the quality specifications. Controller design methods are discussed both for input/output models and for state space models.

Eight lectures have been elaborated and are available in ppt form covering the following topics (https://www.aut.bme.hu/Pages/ResearchEn/ControlTheory):

1. Lecture: Introduction. Systems and control everywhere. Systems and their models. Analysis methods of continuous time linear systems.
2. Lecture: Analysis in the frequency domain. Relations between the time, Laplace operator, and frequency domain.
3. Lecture: Feedback control systems. Stability analysis. Quality specifications formulated in the time and in the frequency domain. Control structures improving disturbance rejection. *PID* controller design.
4. Lecture: State space representation.
5. Lecture: Controllability, observability, state feedback, state estimation.
6. Lecture: Sampled-data (discrete) control systems. Analysis in the time and in the z-operator domain.
7. Lecture: Description of discrete systems in the frequency domain. Relation to the continuous frequency functions. Discrete *PID* controller design. Discrete state equations. State feedback, state estimation.
8. Lecture: Control of discrete systems with time delay. YOULA parameterization. Smith predictor. Dead-beat control. Outlook.

For all lectures, problems are available for the students, which can also be reached on the above link. The students work on them at the last part of the lectures, and then get feedback about the solution and extra points for good solutions.

Recently published Springer textbooks [7, 8] support the learning process. We refer also to the textbook of Åström and Murray [2].

3 Method of Teaching the Basic Control Course

In the 3 hours of the lectures, 2 hours are devoted for lecturing and presentation; in the next hour, the students solve problems and then get immediate feedback of the solutions. During the semester, they have to work on a project designing continuous and discrete controller for a given plant. Besides these lectures, two problem-solving lectures prepare the students for the tests. Every second week, the students solve MATLAB/SIMULINK exercises in the computer laboratory with the guidance of the teacher.

Besides the presentations, visual interactive demonstrations have a convincing strength while providing also the joy of learning. Active problem-solving using software MATLAB/SIMULINK means learning by doing, while the students get some expert knowledge in analysis and design of control systems.

Laboratory work in the next semester is also very important. Use of distant or virtual laboratories would be also beneficial.

4 SYSBOOK Platform: Interactive Demonstrations

The idea of T. Vámos dating back for 20 years was to present the main principles governing systems and control on different levels, for everyone, for students, and for control experts [3, 11–13]. Nowadays there is an increasing demand to explain these concepts to everyone, simply and especially for non-engineering students [1].

System view could give a new dimension how to look at the phenomena around us. It could be useful for experts with nontechnical background as well. With system view in different areas of expertise, the systems could be better understood contributing to better decisions influencing their performance. Besides engineering, such areas are, for example, medicine, medical technics, economy, etc. System view is the basics of control engineering. New concepts in mathematical system theory could open new perspectives to modern areas of control design.

A multilevel e-book has been developed by T. Vámos and coworkers available at http://sysbook.sztaki.hu/. Its cover page is seen in Fig. 1.

The first level – knowledge for everyone (Fig. 2) – appears in cartoon-like form with explanations. The second level gives deeper explanations with mathematical descriptions for the students. Some animations and interactive files demonstrate the main concepts. Some pages are devoted to the third level dedicated for experts.

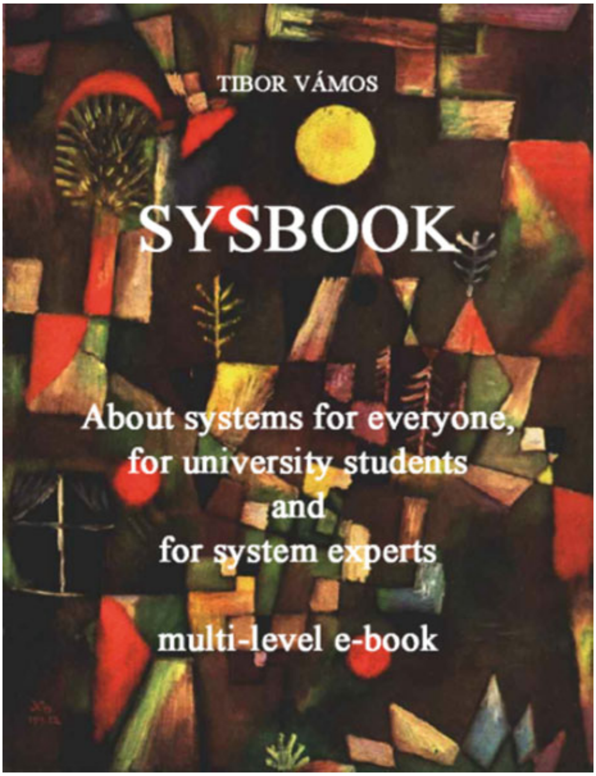


Fig. 1 Cover page of SYSBOOK

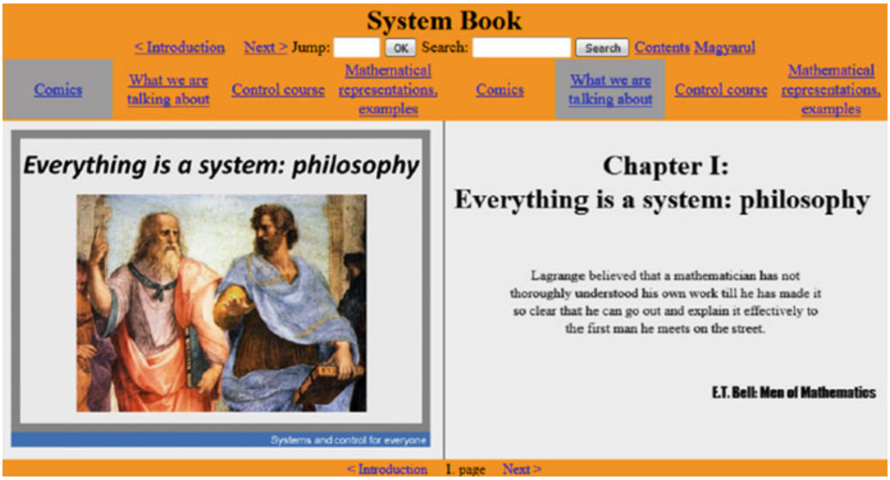


Fig. 2 Basic ideas can be explained for everyone. (Raffaello: The School of Athens, detail)

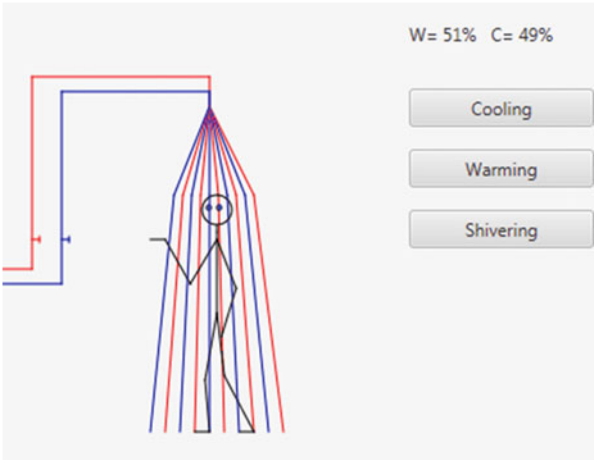


Fig. 3 Taking a shower may be a difficult process (Java applet)

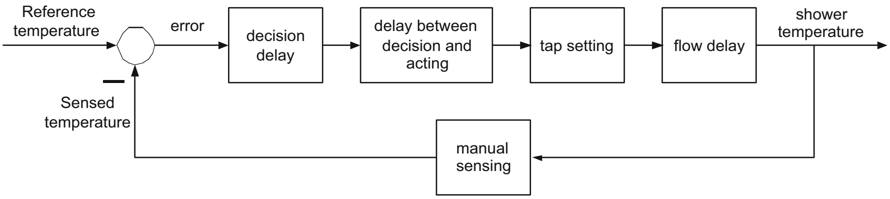


Fig. 4 Control is based on negative feedback

The pages of SYSBOOK appear on different surfaces that depend on the reader's interest. Four categories are distinguished: comics; what we are talking about; control course; and mathematical representations and examples. Two surfaces do appear at the same time. The reader may navigate among them.

Case studies illustrate how system view and control disciplines can be applied in different areas (e.g., cooking, driving a car, energy production, oil refinery, some aspects of economy, systems and control in the human body, feedback in education, etc.).

SYSBOOK includes some demonstrative and interactive files visualizing system behavior. During the lectures, these parts of SYSBOOK can be used for demonstration. The case studies can be samples for the own work of the students.

As an example, Fig. 3 demonstrates that control of a system can be a difficult task. Taking a shower (Java applet) requires appropriate actions when changing the position of the taps considering the time delay of the process. Control is based on negative feedback, compares the measured output variable with its reference value, and uses the difference to modify the input variable of the system (Fig. 4).

If the action does not take into consideration the effect of flow delay, unstable performance could take place, and the temperature will change between hot and cold. By modeling the blocks and analyzing the behavior of the closed loop, some consequences can be drawn how to manipulate the system.

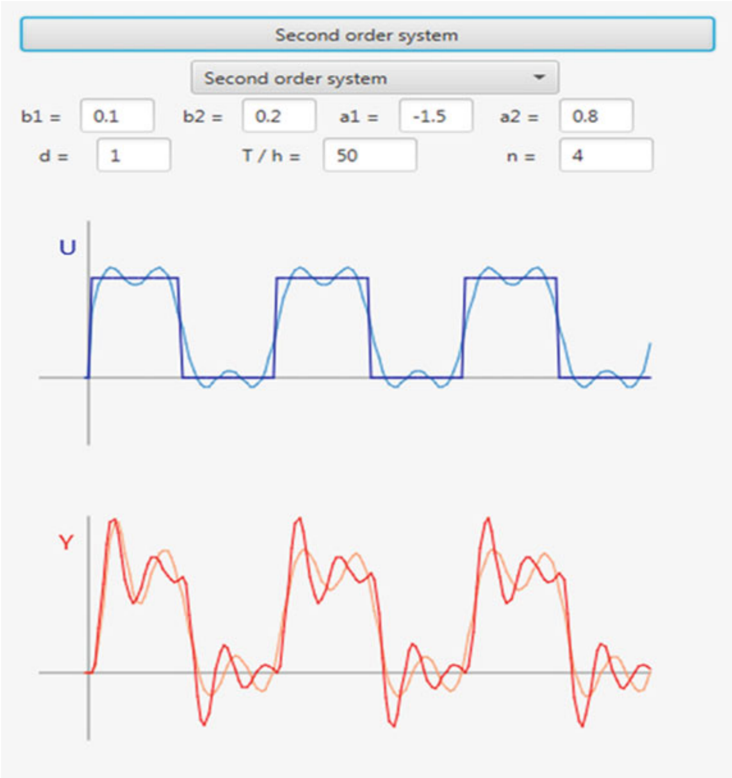


Fig. 5 Demonstration of the relationship between the time and the frequency domain

The behavior of systems can be analyzed in the time, frequency, and operator domain. The relationship between analysis in the time and in the frequency domain is illustrated by the interactive Java applet shown in Fig. 5. It presents that taking more sinusoidal components in the periodic input signal, the output of the system will be better approximated by the sum of the individual output components. The parameters of the system and the number of the sinusoidal components can be changed and the responses are visualized. So it is convincing that from the frequency response, consequences can be made for the time response of a system.

Another Java applet calculates and visualizes the step responses and frequency functions (Nyquist and Bode diagrams) of different systems.

Several control algorithms are discussed. Their behavior is demonstrated analyzing how the system tracks the reference signal, how it rejects the effect of the disturbances, how parameter uncertainties influence the performance, and what is the effect of the filters. Figure 6 demonstrates the behavior of a control system with *PID* controller. It is mentioned that MATLAB/SIMULINK ensures a better platform for controller design during the computer laboratories.

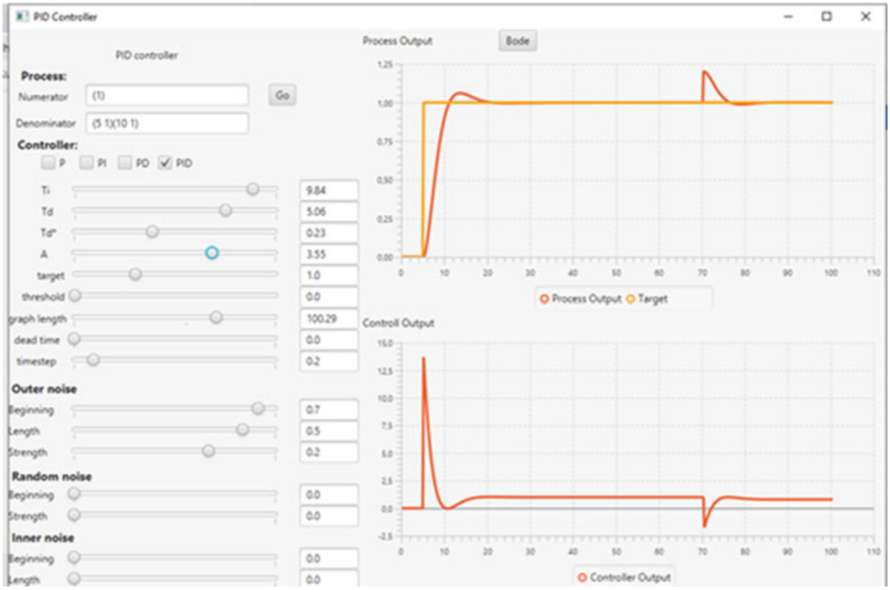


Fig. 6 Interactive Java file demonstrating the behavior of *PID* control

We refer here also to the interactive tools developed by Guzmán et al. [5, 6] for controller design.

5 New Paradigm in the Basic Control Course: Youla Parameterization

As a new feature, YOULA parameterization has been introduced as an essential control idea in the basic control course [9]. This approach follows from the basic feedback control idea and provides good properties for the control system especially in case of big dead time. The basic idea is shown in the sequel.

Control is based on negative feedback. In the theoretical part of the curriculum, properties of negative feedback are discussed. The block diagram of the control structure is shown in Fig. 7, where P is the model of the plant to be controlled, C is the algorithm of the controller, and F is the input filter.

This structure is effective ensuring reference signal tracking and disturbance rejection. The controller C is designed for the model of the plant considering the quality specifications. The most frequently applied algorithm is the *PID* controller.

Supposing a unity filter F an equivalent structure between the output y and the input r is given in Fig. 8. Q is called the YOULA parameter. Reference signal tracking would be ideal if controller Q would realize the inverse of the process model.

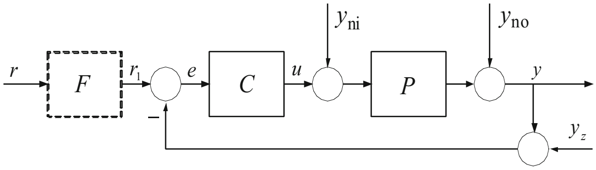


Fig. 7 Control is realized by negative feedback

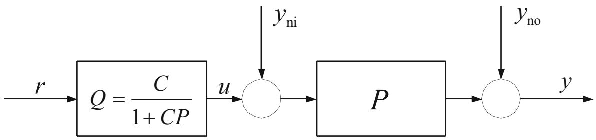
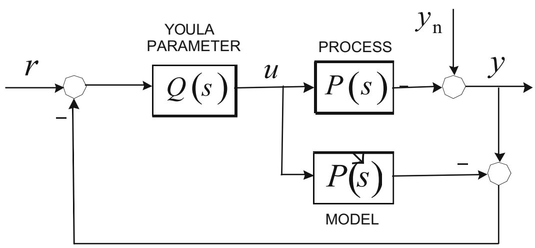


Fig. 8 Equivalent control structure with the YOULA parameter

Fig. 9 YOULA parameterized control with IMC



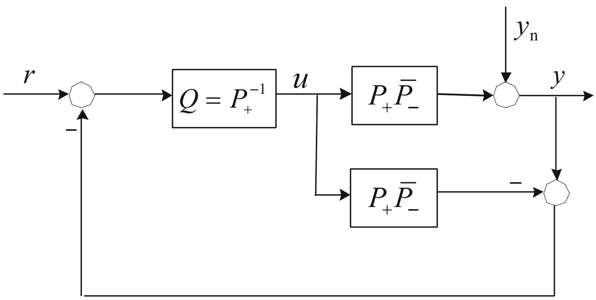


Fig. 10 Realizable YOULA parameterized control

But this structure cannot reject the effect of the disturbances. Therefore it is enhanced with Internal Model Control (IMC) [4] according to Fig. 9.

YOULA parameterized control can be used to control stable processes.

Generally the inverse of the process cannot be realized. The process model P should be separated to the invertible P_+ part whose poles can be cancelled and to the non-invertible part $\overline{P}_-$ which contains the dead time and the non-cancellable poles. The YOULA parameter realizes the inverse of the invertible part of the process model (Fig. 10).

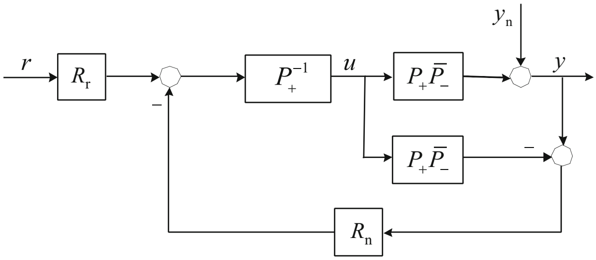


Fig. 11 YOULA parameterized control enhanced with filters

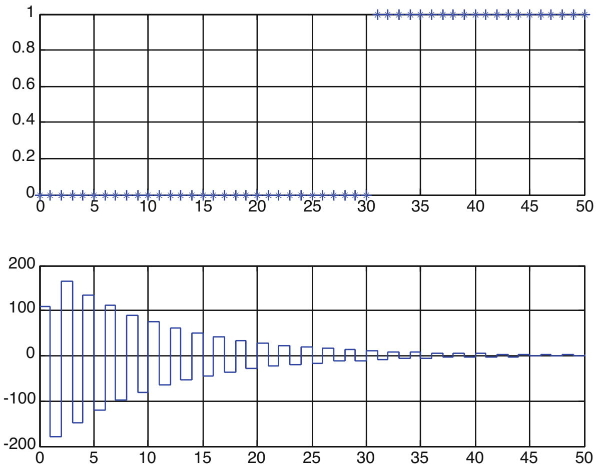


Fig. 12 Output and control signals when Q parameter cancels the whole dynamics

This structure can be enhanced by the R_r reference and R_n disturbance filters according to Fig. 11.

The role of the filters is threefold: the dynamics of reference signal tracking and disturbance rejection can be different (*2DF*-two-degree-of-freedom controller), the maximum value of the control signal u can be restricted, and by appropriate choice of the filters, the control system can be made more robust, i.e., more insensitive to model uncertainties.

This structure can be applied both for continuous and discrete systems. For discrete systems, instead of the transfer function P the pulse transfer function G is used.

Figure 12 shows the output and control signals for control of a discrete second-order system with big dead time when cancelling the whole dynamics. Oscillations in the control signal will cause intersampling oscillations in the output signal, while reaching the required reference value in the sampling points. Figure 13 gives the

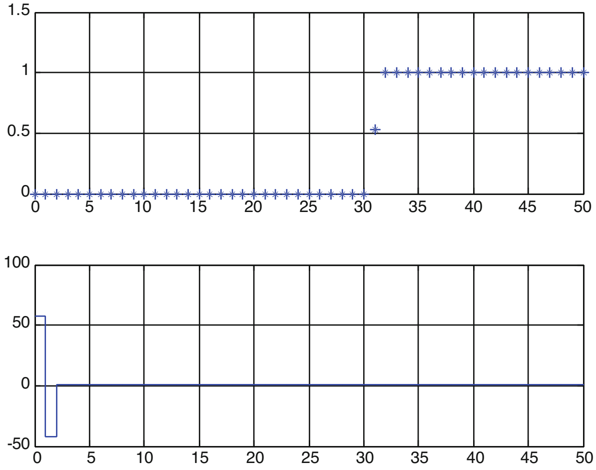


Fig. 13 Output and control signals when Q parameter cancels only the invertible part of the model

signals when only the invertible part is inverted in the controller. It is seen that the control performance became calm. Here filters were not applied.

The YOULA parameterized algorithm is especially effective when the process contains big dead time, and with appropriate design of the filters it is less sensitive to parameter uncertainties than the other algorithms.

It is shown that other control algorithms as *PID*, Smith predictor, and dead-beat control can be considered as special cases of the YOULA parameterized algorithm.

6 MATLAB/SIMULINK Computer Exercises

The basic software applied in the computer laboratories is MATLAB/SIMULINK. The students get some expertise in applying analysis and synthesis methods in problem-solving.

A MATLAB exercise description gives a short summary of the considered topic and then provides the examples from the simplest to the more complex ones. A MATLAB exercise related to a given topic can be executed within a 2 hour time frame and provides the knowledge for further individual work in the given topic. The students generally do not get a ready program; they have to build it command by command. This way, they have to think over and understand the analysis or design procedure step-by-step. Based on these exercises, the students are prepared to solve basic control problems and to solve the homework project. The MATLAB exercises cover the following topics: Introduction to MATLAB/SIMULINK and to the control toolbox. Properties and characteristics of typical control elements in the time and in the frequency domain. Stability analysis. *PID* controller design. State space description. Controllability, observability. State feedback, state estimation. Sampled data control systems. Z-transform and pulse transfer functions. Controller design based on the YOULA parameterization. Discrete *PID* controller design. Smith predictor. Dead-beat control.

Generally the problem is solved using MATLAB, and then a SIMULINK program is built to simulate the behavior of the control system. In some cases a core program is given for a specific problem, and the students give the input data and running the program they evaluate the behavior of the system.

As an example, the core program of the discrete YOULA parameterization is presented in the sequel.

```
% Youla_discrete basic program
Q=minreal(Rn/Gp,0.0001)
C=minreal(Q/(1-Q*G),0.0001)
L=minreal(C*G,0.0001)
Tr=minreal((Rr/Rn)*Q*G,0.0001)
Ur=minreal((Rr/Rn)*Q,0.0001)
t=0:Ts:50;
yr=step(Tr,t);
subplot(211), plot(t,yr,'*'),grid
ur=step(Ur,t);
subplot(212), stairs(t,ur),grid
```

Then the user defines the process (e.g. second-order system), gives the sampling time, calculates the pulse transfer function and gives its separation to invertable and non-invertable parts, and gives the filters. The MATLAB code is:

```
clear; clc; s=zpk('s')
P=1/((1+5*s)*(1+10*s))
Ts=1; z=zpk('z',Ts); G1=c2d(P,Ts)
G=G1*z^(-30)
Gm=1;    %G_
Gp=G1/Gm    %G+
Rr=1/z; Rn=1/z;
```

Then call the program. The behavior of the algorithm can be investigated with different separation and with different filters. The program can be enhanced by calculating the responses for the disturbances as well. The SIMULINK diagram can be built (Fig. 14) enabling analysis of intersampling behavior as well.

The MATLAB exercises supporting the control course are given in Keviczky et al. [8]. The chapters of the exercise book are fitted to the chapters of the theoretical material.

7 Open Content Development: Student Case Studies

Nowadays in education a new teaching-learning paradigm is Open Content Development (OCD) which means active participation of the teachers and students creating an up-to-date teaching material. This project runs at the Department of

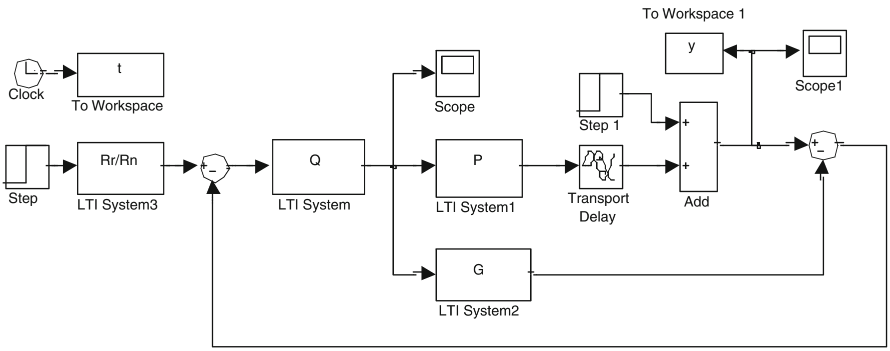


Fig. 14 SIMULINK program for the YOULA parameterized control system

Technical Education at the Budapest University of Technology and Economics since 2015 supported by the Hungarian Academy of Sciences [3]. In the frame of vocational teacher training programs, several so-called micro-contents have been developed. Utilizing the experiences of these pilot efforts, this approach seemed to be fruitful also in basic control education.

The SYSBOOK platform has been connected to the OCD model. SYSBOOK provides several case studies for systems and their control. Teachers and students studying systems and control can elaborate new case studies in their areas of interest which means active application of the learned topics. After evaluation these projects can be uploaded in the student area of SYSBOOK.

The system chosen by the students is modeled. The control tasks are formulated. In the different examples it is investigated, what is the considered system, how is the system connected to its environment, what are its input signals, and what are its output signals? What happens between them? How can this be described mathematically? What are the requirements set for the system? Can we control the system? How to control the system?

Some uploaded student projects are temperature control of a terrarium, speed control, model of the blood circulation and the respiratory system, the model of building a house, etc. (Fig. 15). Every semester, the student area is supplemented by new case studies.

The system open for the participating students/learners and educators is accessible through the research web page (www.ocd.bme.hu); the page also contains bring your own device (BYOD) approaches that serve the methodological support of the innovations implemented within the open system.

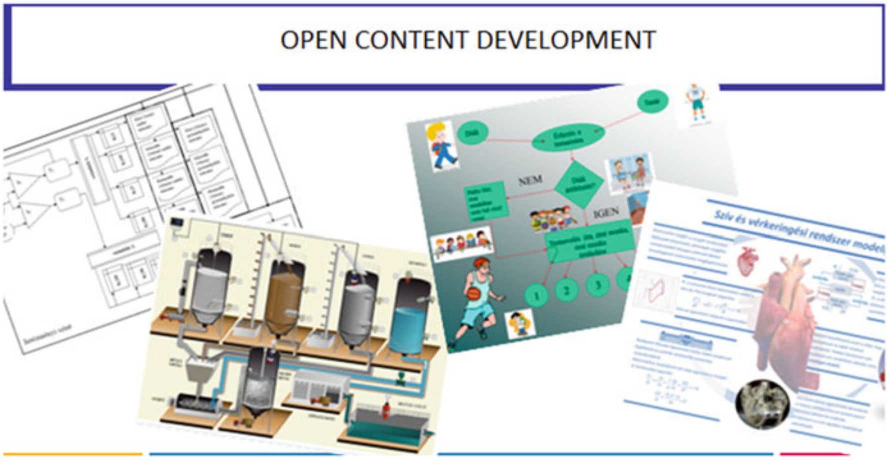


Fig. 15 Some student projects

8 Conclusions

Nowadays considering the ever-increasing knowledge, the explosion of information available at the Internet, the available visual technics and software tools, and the requirements for online education, there is a need to revisit the content and the teaching methodology of the basic control course.

Eight lectures have been elaborated which are available for teaching. Corresponding problems with the solutions are also provided.

As a new paradigm, controller design based on YOULA parameterization has been introduces already in the first control course. It is shown that some other control algorithms can be considered as special cases of YOULA parameterization.

In the methodology of teaching, a basic control course the motivation of the students can be increased by active participation in the learning process, including interactive demonstration of the principles, solving exercises at the end of the lectures, solving analysis and synthesis problems in the computer laboratories, and developing own case studies for SYSBOOK in OCD framework.

It should be also emphasized that the examples of systems and their control should be chosen mainly from the area of the specialization of the students (electrical or software engineering, chemical engineering, biology, economics, etc. [10]). Also it is important to provide real-time experiments in laboratory work or using distant laboratories. IFAC Repository would be also of great help reaching useful resources.

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