Modular Approach to Teaching PID Control

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***Abstract*—This paper describes a blended learning approach in teaching "Constrained Time-Delayed Proportional–Integral–Derivative Control." It is based on the "learning by doing" paradigm supported by several e-learning tools: by the interactive electronic course materials in Moodle; by the laboratory of low-cost and easy-to-manipulate plants; and by the virtual laboratory WebLAB. These open the access to study and experiment on real systems via Internet for 24 h/day, seven days a week. Synergy of the newly structured theory developed to deal with real-world constraints with the interactive content delivery and with active learning based on simulations, real-time experiments in laboratories, and tele-experiments via Internet offers stimulating and quasi-authentic learning environment. These give students multiple formative feedback, ranging from computer quizzes to plant reactions in a rich variety of authentic situations.**

***Index Terms*—Computer-aided instruction, control engineering education, courseware, user-centered design.**

I. Introduction: What, Why, and How?

THE COURSE "Constrained Time-Delayed Proportional–Integral Derivative (PID) Control" is dedicated to advanced-control-engineering students at masteral or doctoral levels, to research workers and industrial control engineers, and to anyone interested in application-oriented research. It is carried out with emphasis on good matching of theory and practice. It gives a chance to understand, experience, and handle PID control design studied from multiple points of view, involving real plant control properties and constraints.

The aim of the course is to explain and practice basic principles of the PID control and its application. The instructional design includes all important steps: from absorbing the general theory covering all key factors of the design (constraints, time delays, measurement noise, disturbance compensation, and dynamics fluctuations) to the control analysis based on computer simulation and real plant identification, to the verification of design via measuring real closed-loop properties.

Based on the "learning by doing" or "learning by experimenting" strategies in a quasi-authentic context, it adopts the constructivist philosophy [23] of the student-centered e-learning, or blended learning. The course participants are supported by:

1) printed textbooks ([1], [10], [11]) with many examples and exercises, and summaries and reflection points;
2) conference papers and other Internet resources;
3) electronic course materials (available via learning management system Moodle, http://elearn.elf.stuba.sk/moodle/course/view.php?id=23) containing:
   a) Matlab/Simulink, or Scilab/Scicos programs for simulation and control experiments;
   b) FLASH and JAVA animations of basic problems;
   c) e-books;
   d) tests for self-evaluation;
   e) low-cost and easy-to-manipulate physical models of real plants that are either sent or given to each student or made accessible via Internet;
   f) manuals to all required activities;
   g) face-to-face workshops (if required by students);
   h) tutors.

PID control is a term usually used for denoting the control with the *P*roportional, *I*ntegral, and *D*erivative action that has been, for decades, the most common control technique used in process control. Despite the relative simplicity and long history, the fact that there are several hundreds of "optimal" tuning of PID controllers [21] indicates not only complexity of control problems, which cannot be easily segmented, but also some unsolved problems in this area. Great numbers of engineers and scientists are therefore looking for newer solutions that are expected to offer better performance than the PID control does. The new solutions are generally more complex and based on computational power of available computers, e.g., the predictive, neural, and fuzzy control.

This course tries to explain "simple" problems of the PID control in a simple way. Hence, it restraints (when appropriate) on "global" mathematical formalism, or "fuzzy" and other "advanced" approaches. It stresses active experiments (both the computer simulations and the real time control), reflection, and observation. This helps to integrate many up-to-now isolated fractions of experience which is developed by practitioners, and control and process engineers into a compact and "practical" theory, by showing possible generalization, thus helping the industrial design process to become more efficient and effective and to respond to new challenges of practice.

The controller analysis goes back to the origins of the first feedback structures of the PID control. In addition to explaining the basic well-known properties and standard solutions, several new structures have been derived giving excellent results in some special situations. Choice of a proper structure for a given situation can reasonably increase the design reliability

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and lead to a unique optimum. In this way, the multidimensional inflation of different optimal tuning formulas, antiwindup (aw) structures, discretizations, and controller forms are the results of using inappropriate control structures that do not take into account the dominant process parameters and, thus, cannot guarantee a globally optimal solution to the problem.

Development of the PID control started without any theory about 100 years ago. It was mostly based on experimental and intuitive work of engineers in several development centers. The first period was dominated by pneumatic and analog electronic controllers based on high-gain amplifiers with feedback structures. The integral (I) action originally called as "automatic reset" was used to reset the controller output to achieve zero steady-state error. Later on, the control theory has undergone rapid development. Invention of microprocessors in 1980s caused revolution in the control technology and a birth of "pure" integrators. Then, it was really pertinent to speak about integral control. However, the "physical" appearance of integrators led to dramatic problems with the integrator windup. The increased independence of these new solutions from hardware was expected to decrease the diversity of developed solutions formerly caused by different hardware approximations of "ideal" controllers for different ranges of adjustable parameters. However, in fact, the opposite turned out to be true—it further contributed to inflation of existing solutions, e.g., by leading to different discretization rules used by particular producers.

One possible solution in avoiding the windup problem uses the disturbance observer (DOB) that regards the difference between the actual (identified) plant input and the output of the controller as an equivalent disturbance. The estimated equivalent disturbance is utilized as a compensation signal. In motion control, the DOB concept was introduced and applied in different modifications by Ohnishi *et al.* [12]–[15], [26]. Umeno and Hori [28] developed the DOB theory by the factorization approach. DOB is now used in many high precision motion control systems [9], [19], [29], e.g., in disk drive servo control, or controlling robots in contact with environment (precise assembly, grinding, deburring, obstacle avoidance, teleoperation, etc.). DOB-based force control enables to improve the traditional tradeoff between the stability and the response dynamics that is one of the fundamental prerequisites for evolution of human-cooperating robots [13] with haptic ability that will have an important role in the future aging society. Ohnishi *et al.* consider the DOB-based force control as a major breakthrough in force technology that has broken down the wall which conventional technology could not overcome.

The estimated disturbances are effective not only for the disturbance compensation increasing the system robustness but also for the parameter identification [13]. Due to the transparent relationship between performance criteria and gain selection, the DOB structure allows simple and intuitive tuning of its gains that is practically independent of the state feedback gains. This explains why DOB is so welcome by control practitioners. The only known limitation of the DOB concept is that it cannot be directly applied to systems with a nonminimum phase zero.

Similar consequences can be also met in applying the DOB-based controllers in solving the simplest control tasks that were traditionally solved by the PID control: the improved tradeoff between the stability and the response dynamics, loop simplicity enabling simple and intuitive plant identification, loop tuning and also consideration of constraints put on the control signal. It can be shown that the introduction of the DOB-based disturbance compensation is equivalent to introduction of a windupless integral action.

This paper is organized as follows. Section II summarizes motivation for teaching PID control in an innovative way. Section III gives short characteristics of a new modular approach to the "Constrained Time-Delayed PID Control." Section IV outlines basic implementation principles. The virtual laboratory WebLAB and the client applications used are described in Section V. Practical experience developed while delivering the course and the conclusions are the focus of Sections VI and VII, respectively.

II. Inflation of Controllers and Tuning Rules

The inflation of different controllers is far from being the only confusing phenomenon. After several decades of development in the area of the PID control, the present situation can be characterized by hundreds of "optimal" tuning rules (gathered, e.g., by O'Dwyer [21]). This degrades the term "optimal" so that for the user it may give nothing.

At the same time, we may also see numerous approaches trying to avoid inflation of PID tuning by developing general parameterized solutions that can be relatively easily adjusted to a particular situation—see, e.g., the works of Åström *et al.* [1], [2], who build on parameterizations as the sensitivity functions, or the complementary sensitivity functions that are related to the robust control. By having a clear-cut physical interpretation of the effect of such tuning parameters and clear picture of its appropriate default values, the tuning should be much simpler and reliable.

However, there are still several signals that the sensitivity function does not represent the final and optimal solution. It might be expected that by decreasing the range of possible parameter changes, the effect of the nonmodeled dynamics (parasitic delays) and the amplitude of the measurement noise—when there are no other specifications on the control quality, only the settling time—the achieved tracking dynamics would converge to that of the minimum time control and the disturbance rejection would be ideally perfect. This requirement, which is obviously not met by the sensitivity functions, was approached using another way of the closed-loop parameterization—the pole assignment method by Glattfelder and Schaufelberger [7]. They tried to design the PI controller in such a way that, by shifting the closed-loop poles to $-\infty$ (or the cutoff frequency to ∞), its control signal step reaction would converge to the one pulse of the minimum time control. The first problem they had to overcome was that of the controller windup, where inflation of different solutions can be found again.

The second serious discrepancy arises from the obvious inconsistency of the optimal controller specification when comparing the works of Glattfelder and Schaufelberger with those of Klán and Gorez who require the optimal PI control setpoint

TABLE I
BASIC CONTROLLERS AND APPROXIMATIONS TREATED WITHIN THE COURSE

		Dominant dynamics							
Dynamic class	I-action	K	Ke^{-T_d}	$\frac{K_s}{s+a}$	$\frac{K_s e^{-T_d s}}{s+a}$	$\frac{K_{s1}}{s+a_1}+\frac{K_{s2}}{s+a_2}$	$\left[\frac{K_{s1}}{s+a_1}+\frac{K_{s2}}{s+a_2}\right]e^{-T_d s}$	$\frac{K_s}{s^2+a_1 s+a_0}$	$\frac{K_s e^{-T_d s}}{s^2+a_1 s+a_0}$
0	N	FF	FF	FF	FF	FF	FF	FF	FF
	Y	I	PrI	PI	PrPI	PID	PrPID	PID	PrPID
1	N	-	-	P	PrP	P-P	PrP-P	PD	PrPD
	Y	-	-	PI	PrPI	P-PI	PrP-PI	PID	PrPID
2	N	-	-	-	-	-	-	PD	PrPD
	Y	-	-	-	-	-	-	PID	PrPID

FF = Static feedforward control – it is also involved in all feedback structures
Pr = Predictive (Dead Time) Controller

step reaction to have a stepwise character (see, e.g., [17], or the discussion in [27]). Who is right in this conflict?

III. MODULAR APPROACH TO PID CONTROL

The answer to the previous question seems to be elusive: both parties are right, but just not completely right. The course tries to show why and how it is possible. After demonstrating why the traditional linear solutions fail, new simple solutions are explained using a clear physical motivation, which is experimentally verified and analytically proven. They are parameterized by the closed-loop poles (cutoff frequency or time constants) in such a way that, by limiting the poles to $-\infty$, they converge to the results of the minimum time control.

A clear definition of the limit loop behavior requires introduction of several dynamical classes (DCs) of control which have to be separately treated. These are denoted by a performance index giving the number of saturated pulses in the optimal control reaction to a reference signal step. Introduction of DC then automatically leads to modular approach to the PID controller design. This is interpreted as control of plants with dominant dynamics up to the second-order + the dead time (see Table I).

Processes of the DC0 can be found in situations where the dynamics of transients may be neglected, i.e., they are not connected with a reasonable energy accumulation and aimed at balancing the required steady states under acting disturbances. Such processes can be observed in controlling flows by valves, or in controlling the concentration of oxygen remaining in the exhaust gas for controlling efficiency of the combustion process in an engine [24]. The ideal control signal response u_o (Fig. 1) to a reference step also has the step character (as required by Klan and Gorez).

After constraining the rate of change in the control signal, the transition to a new control signal value can be an exponential one. After also constraining the second control signal derivative, it takes the form of an S-shaped function. Since for the properly dimensioned actuators and for admissible inputs the control constraints will never be exceeded, these control loops are traditionally well treated within the framework of the linear control theory.

Within the DC1, the time optimal control signal reaction u_o to a setpoint step change involves one control interval with constrained control value (as required by Glattfelder and

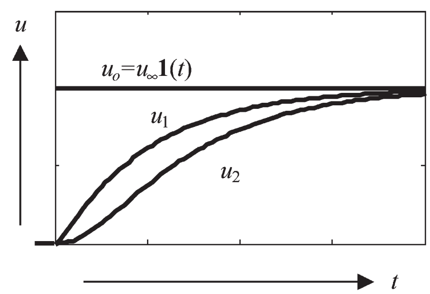

Fig. 1. DC0: control signal reaction to a setpoint step. u_o—without rate constraints. u_1—with a rate constraint put on u. u_2—with constrained second derivative of the control signal u. $\mathbf{1}(t)$—unit step.

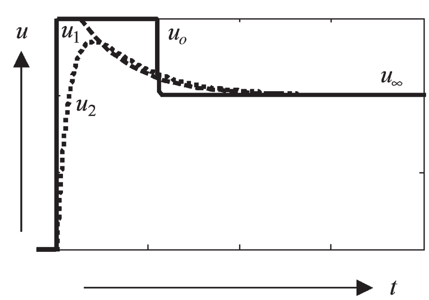

Fig. 2. DC1: control signal reaction to a setpoint step change. u_o—time optimal (without rate constraints). u_1—with rate constraints for the transient from the limit to the steady-state value. u_2—same as u_1 but with an additional limit on the control signal increase.

Schaufelberger, Fig. 2), which is later followed by a monotonous transient to the new steady-state value u_∞. In the initial phase of control, an accumulation of energy associated with a gradual increase (decrease) of the controlled variable y is typical. The fastest growth is achieved under the impact of the limit control signal value. For example, by charging a container with liquid, in the first phase of control, the input valve will be fully open. Only in the vicinity of the required level will the input flow decrease to the steady-state value necessary for keeping the required level. Similar transients can be frequently found in the speed control of mechatronic systems, e.g., in the temperature, pressure, and concentration control.

A typical representative of this DC is the PI_1 controller proposed as the P controller extended by a static feedforward and an inverse model-based disturbance reconstruction and compensation.

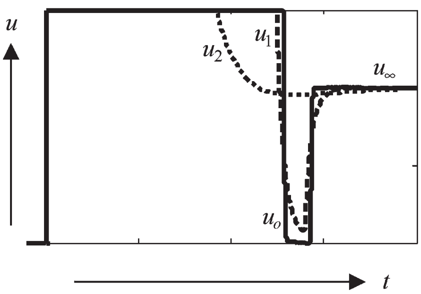

Fig. 3. DC2: control signal reaction to a setpoint step change. u_o—time optimal (without rate constraints). u_1—by limiting rate of changes in transient from one control limit to the opposite one and in transient to the steady state. u_2—same as u_1 but with stronger constraints.

After limiting the rate of changes during the control signal decrease to the steady state (Fig. 2, response u_1), the duration of the limit control action decreases, whereas the total length of transient to the new steady state increases. When also constraining the rate of the control signal increase (response u_2), the control signal may not reach the limit value, since the necessary control decrease to the steady state has to start yet before it—the length of transient—further grows. Although the single interval of control is still visible, by constraining the rate of the change in the control signal, the control reaction slowly approaches a shape that is typical for the lower dynamical class DC0.

With respect to one possible interval with constrained output for dealing with this DC, it is usually not enough to remain within the linear control. Typical solutions for this DC are frequently achieved with different aw controllers (see, e.g., [1], [7], [18], and [25]). It is interesting to note that although these methods usually declare that their "mission statements" are "to suppress the effect of the control signal saturation" and "to recover the linear behavior," they often yield better performance than the original linear control. This means that: 1) they actually do not obey their mission and 2) there is no generally accepted definition of aw. Both these facts result in many different approaches to the problem, misunderstandings, and discussions about the resulting control quality, as in [8] and [20].

Within the DC2, the optimal control signal reaction u_o to a setpoint step already involves two control intervals (Fig. 3) with the control value subsequently constrained to the upper and lower limit value (or conversely) that are later followed by a monotonous transient to the new steady-state value u_∞.

According to the Feldbaum's theorem, the time optimal control is typical with two (rectangular) control pulses with limit control values (Fig. 3). After introducing the rate constraints for both the switching from one limit value to the opposite one and for transient to the steady-state value u_∞, the second control interval is typically rounded, or may even disappear. Therefore, for stronger constraints, the response u_2 again typically converges to the next lower DC.

In the case when the rate constraints allow the control signal to attack both the upper and the lower control limits, also the majority of aw—approaches fail. The windup phenomenon is not only connected with the integral (I) action but also with the controlled process, when it is denoted as the plant windup [7]. For all that the needs for such solutions are very high—let us only mention the automotive industry. Here, when the time optimal control under given constraints on speed and acceleration rate is required, the historically known cascaded linear structures [7] are not able to sufficiently meet the expectations. The sliding mode control (e.g., [6]) is indeed able to guarantee time-suboptimal transients, but the dynamics cannot be flexibly modified in a wide range from the fully linear up to the on–off control transients. One of the earlier attempts used for robot control [21] was based on variable structure systems [16]. The explicit predictive controllers [5], which have been recently developed for constrained processes, require a precalculation of the optimal control and so they are mostly not appropriate for the relatively fast processes with variable parameters and disturbances. In case of such time-variant systems, unless implementing a real-time tuning of PIDs, e.g., an adaptive scheme, the closed-loop robustness is inescapably compromised as well. Simple and reliable solution for this DC, which would enable an arbitrary dynamics shaping, ranging from the fully linear one up to the on–off minimum time control, can be found in [10] and [11].

In all the DCs, the controller design is represented as a *successive approach* based on approximations with increasing complexity (Table I) expressed in terms of the model degree (horizontally) and of the DC index (vertically). Although an increased controller complexity (which is strongly related to the approximation degree and to the DC index) would ideally be expected to lead to increased matching between the plant and the model dynamics, and also to increase control quality, it is in fact accompanied by rapidly increasing sensitivity to the measurement and quantization noise, to the parameter fluctuations, and to the nonmodeled dynamics. Therefore, the rough industrial environment usually prefers the simplest solutions from the DCs 0 and 1 based on the simplest plant approximations. There are still exceptional processes requiring more complex approximations; however, these are not sufficiently solved and popularized until now.

IV. Course Implementation

The single-input–single-output control problems that the course is dealing with are ordered from the simpler to the more complex ones. Higher complexity of some tasks is not only caused by considering the control design for more complex system dynamics but also by considering real-world features (e.g., the measurement noise influence, disturbances, and asymmetric properties of real plant) or by requiring higher closed-loop performance (e.g., for the time-delayed systems).

Due to the successive approximation approach, the course represents a set of case studies devoted to different tasks of the constrained time-delayed PID control. Students can compare and verify sequence of solutions of different complexity with a large number of other well-known, but *ad hoc*, ones proposed by different authors and to construct their own opinion. As various types of materials and tools typical for modern education—including simulation tools and real plants, support the course, students can draw their own conclusions based on their own experience. In this constructive way, by solving real problems in a quasi-authentic environment and collecting

Fig. 4. Thermooptical laboratory plant.

personal experience, the transfer of research results into practice is promoted, and the gap between the theory and practice is well on the way to being decreased.

A. Plant Models

In order to enable each student to actively and individually work in a quasi-authentic framework with real-time experiments, we need to have a large number of plant models which guarantee:

1) clear physical "visibility" of the controlled dynamics;
2) time constants in the range milliseconds to minutes;
3) safe manipulation and easy maintenance;
4) reasonable price;
5) availability of sensors and actuators;
6) connectivity to standard computers without special converter cards and special real-time software;
7) approach via Internet;
8) plants with different degree of "control difficulty";
9) plants offering broader spectrum of dynamics.

As a typical representative of a plant equipped with all the required features, the thermooptical plant (Fig. 4) can be mentioned. This product of several years of development offers measurement of eight process variables (controlled temperature and its filtered value, ambient temperature, controlled light intensity, its filtered value and derivative, the fan speed of rotation and its motor current). The temperature and the light intensity control channels are interconnected by three manipulated voltage variables that influence: the bulb (heat and light source); the light-diode voltage (the light source); and the ventilator (the system cooling). In addition to these, it is possible to adjust two parameters of the light intensity derivator. Currently, more than 30 such plants are used in our laboratories.

B. Control Interface

The plant can be easily connected to standard computers via a universal serial bus (USB), where it allows sampling periods of more than 40–50 ms. The USB communication is also available in controlling three-tank and positional systems.

Within a Matlab/Simulink scheme, the plant is represented as a single block, limiting use of costly and complicated software package for the real-time control. The usual process–computer communication based on a professional converter card is also supported, but it is necessary only for more demanding applications requiring higher sampling frequencies (such as the magnetic levitation control). A similar solution for the open-source Scilab/Scicos is under development.

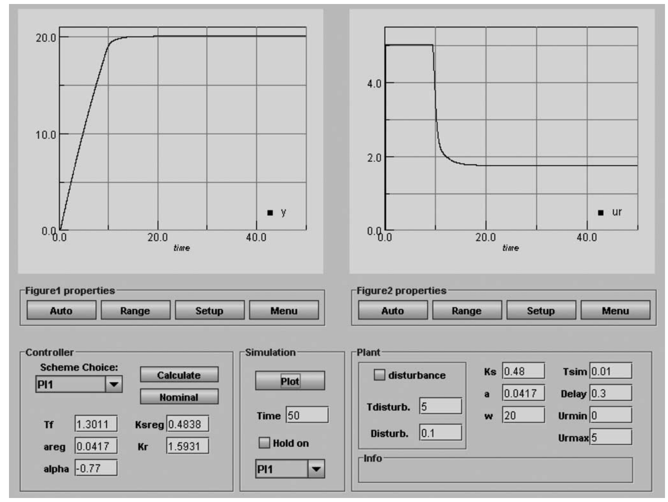

Fig. 5. Graphical layout of an animation applet.

C. Animation Tools

In studying the PID control, a theoretical introduction is needed in explaining: which DCs of controllers we know; how they can deal with various working conditions and quality requirements occurring in a particular application; how they can be tuned; and for which systems it is appropriate to use them. The best way for supporting this introductory phase of learning is to use predeveloped animation tools created in Java and Flash. Students can set a controller they want to use, type in system's parameters, and see their influence on the time responses. One of the developed applets (Fig. 5) is used for visualization of the constrained control in case of the first-order dominant plant dynamics controlled by two DCs of windupless PI controllers or by the aw PI controllers.

V. Virtual Laboratory WebLAB

For a virtual laboratory, two basic approaches exist: 1) a free access laboratory and 2) an authentication-required laboratory.

While looking at an overview of remote laboratories at http://telerobot.mech.uwa.edu.au/links.html, it seems that the first approach—a laboratory with free access—is more popular. A quick access to the real system is the main advantage. On the other hand, in this case, there is a lower security level, the administrator is unable to personalize the experiment, to track student activities, and there is no possibility to book the remote system for a specific date and time.

The remote laboratory WebLAB is considered to be an extension of the traditional control engineering laboratory with experiments carried out, while being present, using courseware based on Matlab/Simulink with different toolboxes (Real Time Workshop, Windows Target, and xPC Target). This extension should enable students to continue their experiments via Internet besides their regular classes.

WebLAB was created in the PHP programming language in cooperation with the MySQL database. This combination guarantees a dynamic character of the virtual laboratory. The whole application was created using the PSPad software and PhpMyAdmin and is designed for MS Internet Explorer. By means of the language module (containing until now the Slovak and English language pack with possible extension to other languages), it provides a built-in opportunity to dynamically change the language.

A. Structure and Security of the WebLAB

The system security requires definition of the access rights. In WebLAB, four user levels are established:

1) administrator;
2) system owner;
3) student;
4) anonymous user.

The system using the *md5* authentication enables only those features that are allowed to be exploited by the user.

B. Administration Level

The administrator may

1) see all registered students and modify their data;
2) enable or disable access to the system for students or for the system owner;
3) allow the system owner to manage the students' access;
4) add new students from a file or one by one;
5) see online students who are currently logged in;
6) control real systems and edit study materials;
7) modify the timetable for students;
8) enable or disable students working on real systems;
9) change their personal data;
10) upload, modify, and publish system.

Only one user at a time may connect to the real system using the timetable module (Fig. 6). Simultaneously, other students may observe the running experiments.

By seeing the list of reservations, other users can book (or delete) 15-min time slots for their own needs (the double reservations for the same date and time are not supported). However, if there are no reservations for a given date and time, anyone can connect to an experiment. During an experiment, there is a notice that the system is occupied. Only the anonymous users are not allowed to book and carry out experiments.

C. System Owner, Student, and Anonymous User

The system owner (an administrator's assistant) may enable or disable students to do experiments that is useful in case when the real system is being repaired or modified. He may also modify texts and upload pictures and system documents, but he is not allowed to use the module for administration of students and to see personal data of other students.

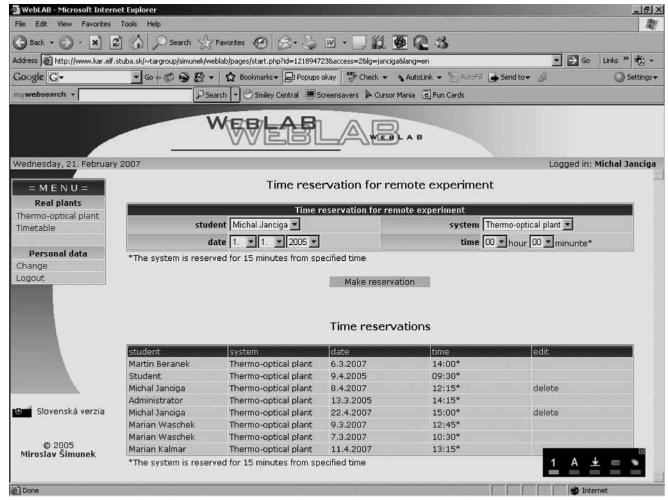

Fig. 6. Timetable module.

Students may see and download the system documents, see the simulations made by the administrator or the system owner, book the system using the timetable module, and carry out the remote experiment. For each system, there is a guide describing a step-by-step procedure of running the experiments and the administrator's and system owner's help including steps that must be taken at the server's side.

Anonymous (not registered) users can enter the system with the login and password "user" and see the information about it. They cannot book or carry out experiments.

D. Client/Server Application

The heart of the client/server application is the server [4]. Its function is to control the Matlab/Simulink program (send commands to it, start and finish experiments) and to communicate with a client (receive commands from it and send experiment data to it). It uses Matlab's Component Object Model (COM) interface—the Microsoft technology defining a language-independent binary standard for component interoperability that integrates the Matlab component to the Java application. Since Java does not naturally support COM, Microsoft SDK was used to integrate them. It contains libraries and compiler for this purpose.

The client part (created by Easy Java Simulations, EJS) serves as a control panel for remote experiments, allowing users to change parameters of an experiment and to display and save data. EJS allows a quick graphical modification without Java knowledge and supports writing custom programming code. This makes it a flexible and effective tool enabling creating custom classes and implementing the whole networking part: connecting to and disconnecting from the server, sending parameters to it, and receiving experiment data.

Fig. 7 shows layout of a client applet with the graphical output (both axes are dynamically scalable) and the plant animation based on changing photos according to the immediate Action signal value. They were taken with step of 0.25 V for the range of 1–5 V.

The left-hand side of the lower half is used for experiment parameters: the name of the Matlab Simulink scheme

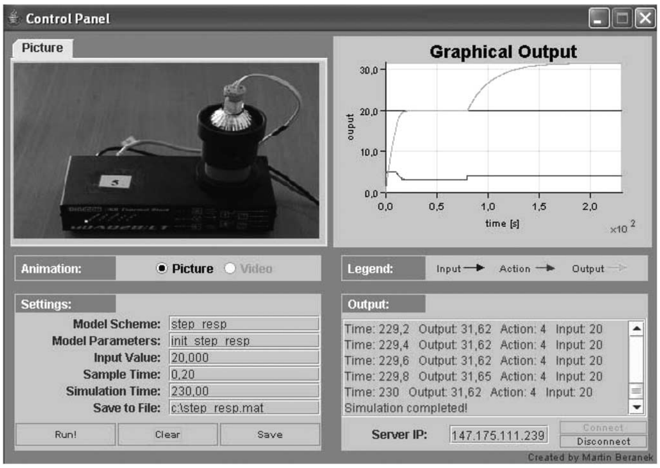

Fig. 7. Graphical layout of client applet with step response of real system.

(.mdl file), name of the Matlab parameters file (.m file), setpoint value, sample time, and duration of the experiment. After finishing an experiment, it is possible to type into the field Save to File the name of the file. The status of transfer can be seen in the Output section.

Before starting an experiment, it is necessary to connect to the server that accepts only one connection at a time and responds with the "Server already in use" statement to the others.

After starting an experiment (by the button Run!), all buttons are disabled—only a graph with an Input signal (setpoint) can be seen, as well as the Output and Action (control) signal. Any errors during the experiment directly sent from the remote Matlab will occur in the Output section.

The Clear button is used for clearing the graph and Output section messages. The Disconnect button finishes the experiment.

VI. Example

One simple task of the course will be illustrated by designing a windupless PI controller of the DC1 (PI_1) for the filtered optic channel of the thermooptical plant. First, the system has to be identified. Then, the control scheme in Matlab/Simulink is designed and uploaded to WebLAB. Finally, the controller is applied to control the real system.

A. Identification

For a simple identification, the system step response is measured by applying a step of a known size to the input of the system brought to a steady state.

In Fig. 8, the system output (filtered optical channel) brought to a chosen steady-state value by a stabilizing controller is exposed at the time of 80 s to a step change $du = 1$ V produced by the input voltage change from 3 to 4 V. The output was measured with the sampling period $T = 0.05$ s up to the new steady state, and the data were saved to a .mat file. After loading it to Matlab on a local computer, the approximation continued by processing the data.

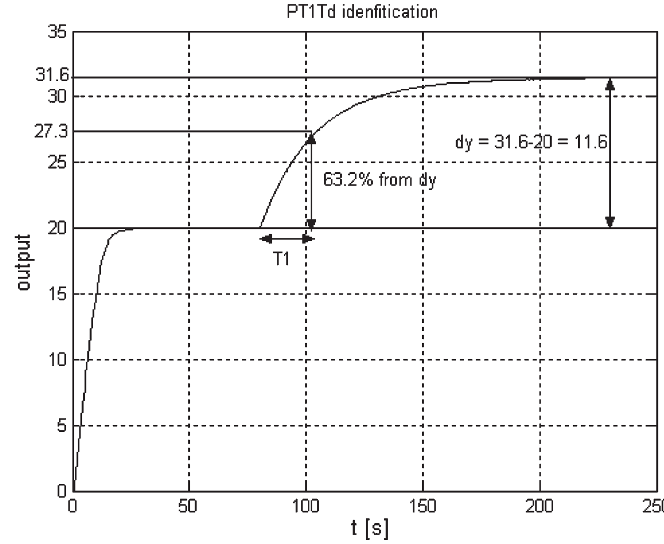

Fig. 8. First-order-lag + dead-time ($\mathrm{PT}_1 T_d$) approximation.

From Fig. 8, the first-order-lag + dead-time model parameters were determined: $dy = 11.6$; $T_1 = 24$ s; $P = dy/du = 11.6$; and $T_d = 0.3$ s (T_d could be determined after zooming the above graph around the step change at $t = 80$ s). This result can be repeated for several working points (to check the plant linearity) and also confronted with results of the other popular identification method—e.g., with the relay experiment [1].

B. Controllers Based on the Identified Model

The windupless PI_1 controller (Fig. 9) is based on constrained P-control extended by static feedforward and DOB-based disturbance compensation using the plant inverse [10], [11]. The main task of P-action tuned by the closed-loop pole α is to speed up the process of reaching the desired value. Similarly, as in [9], [12]–[15], [19], [26], [28], and [29], the I-action of the controller (the reconstructed disturbance) is designed as a difference between the reconstructed filtered plant input and the filtered controller output. By deriving an equivalent controller scheme, it may be shown that this includes structure with P-controller and negative feedback from the saturation output involving the reconstruction filter reported by [1] or [7] as a core of some industrially produced controllers. Stability of the constrained closed loop should be analyzed using the circle criterion and the Popov criterion [7].

By means of the animations and simulations, a student can already break the myth (see, e.g., [25]) that the model-based controllers are less robust and more complex than those using the aw circuitry. Using this scheme and parameters (or the simulation applet from Fig. 5), one gets the experimental results, as in Fig. 10: the transients are fast and monotonous and close to the ideal one pulse of the minimum time control.

The choice of the DOB filter time constant (usually set as the negative reciprocal value of the closed-loop pole, or the reciprocal value of the cutoff frequency) is simply

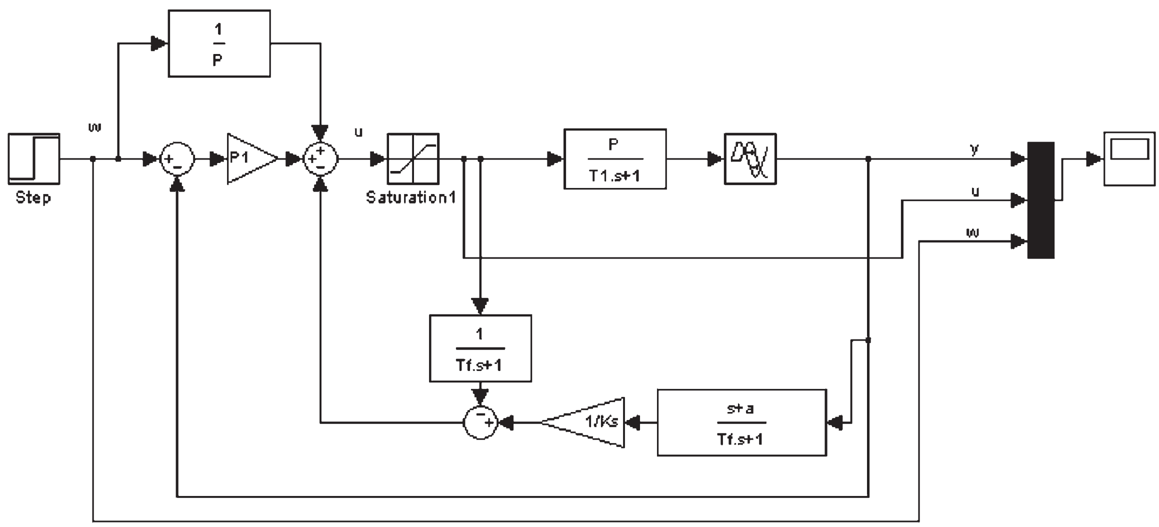

Fig. 9. PI_1 controller—simulation scheme in Simulink.

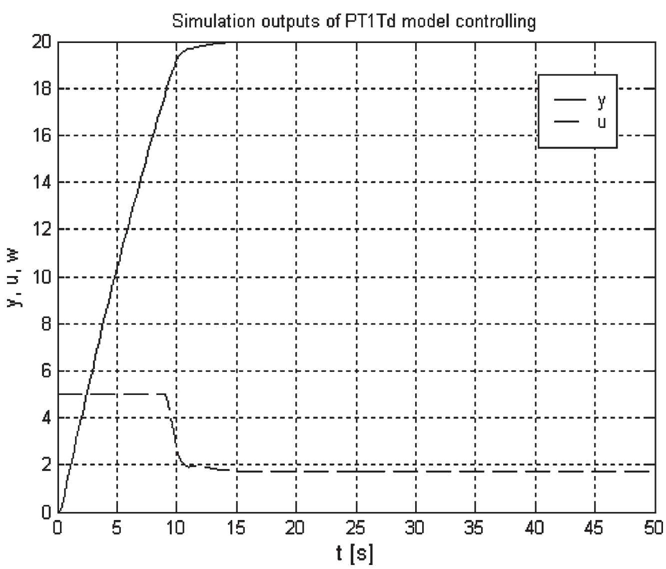

Fig. 10. PI_1 controller—simulation in Simulink for a reference step. y—plant output. u—control signal.

restricted by the identified dead time, whereby according to [10]

$$\begin{aligned} a &= 1/T_1 \\ \alpha &= -0.231/T_d \\ K_s &= P/T_1 \\ P_1 &= -\alpha/K_s \\ T_f &= 4.337T_d. \end{aligned}$$

Next, this controller is verified on the real system. The simulation scheme has to be modified according to Fig. 11—the plant model is replaced by a block communicating with the real system and also extended by a disturbance generator controlling a light-emitting diode (LED). After uploading the scheme and parameters files on the computer with the real system, typing in proper settings to client, and starting the experiment, the results displayed in Fig. 12 were measured. The achieved settling time is slightly longer than that one achieved with the identified model (students have to comment possible reasons for such differences, e.g., changes in the ambient temperature). However, qualitatively, the output transient is still monotonous and close to the expected (simulated) one. The controller successfully compensates the disturbance produced by a step change generated by the LED for $t = 30$. Of course, an arbitrarily large disturbance cannot be compensated due to the limited controller output (0–5 V).

For situations which do not fulfill requirement $T \ll T_1$, discrete time versions of the controller can be used.

Students have to evaluate the differences between models and real systems both from the point of view of a controller tuning and change of the operating point.

The PI_1-controller design is only one of the possibilities in controlling the light intensity. Before approaching it, students start measuring the steady-state input–output characteristics. They design the static feedforward control, I- and PI-control of the DC0, and the aw control according to [7]. They can also continue to higher order plant approximations and to the higher order DCs, and then evaluate what they obtained from the control quality, complexity, and reliability of the controller tuning view.

After that, students proceed in controlling the thermal plant representing a more complex problem which is close to the system with fast and slow modes described in the benchmark examples [3].

VII. Conclusion

As was shown in this paper, the aim of the course on “Constrained Time-Delayed PID Control” was to create a stimulating learning environment that can help students understand the basic principles and provide training in all the steps of the control design required under real constraints for simple plants with dominant dynamics up to the second-order + dead time.

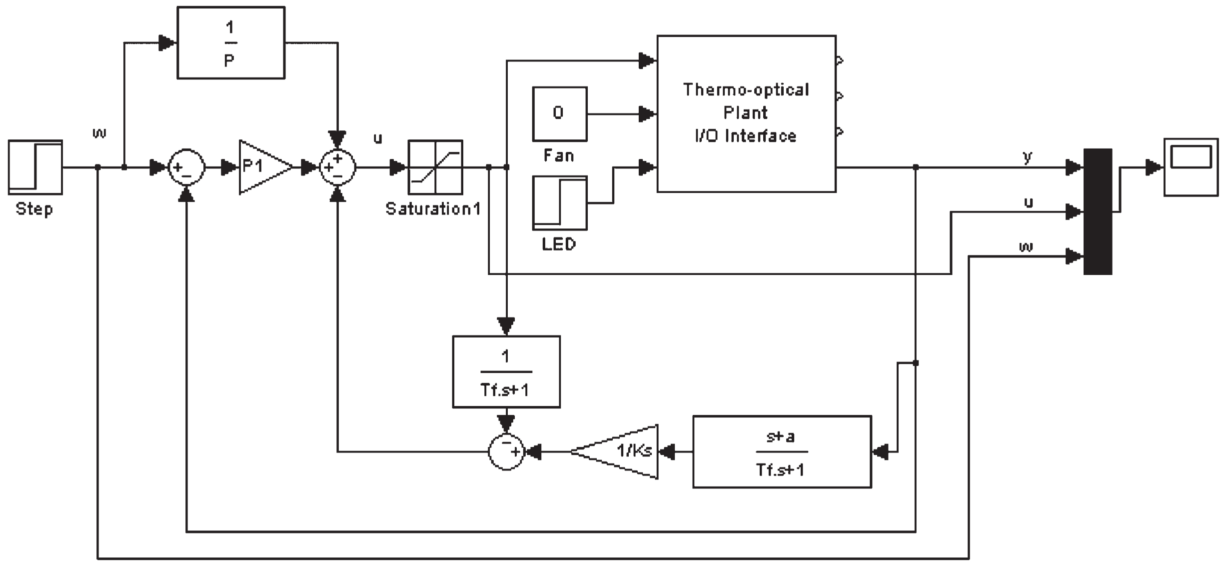

Fig. 11. PI_1 controller scheme for the real-time control.

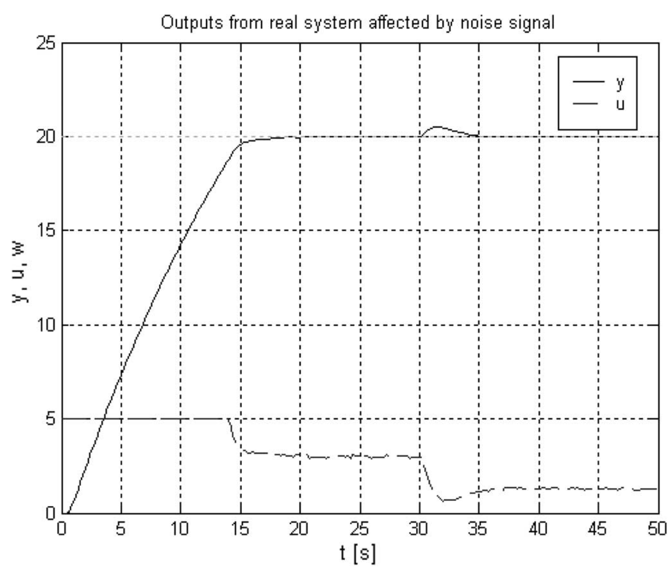

Fig. 12. Outputs from real system with a disturbance step plotted by Matlab.

The control problem formulation was not only limited to: "Having the process transfer function, the performance criteria and limits on the admissible process parameters, what is the optimal controller?" Instead, the aims of the course were to show that for each process, it is possible to achieve a family of models and controllers with different complexity degree, and only after a deeper analysis and verification is it possible to decide which solution is the most appropriate for the practical application.

Although most students have considered that deep mathematical background without practical experience as not well balanced and unattractive, the increased interest in this blended learning course applying the philosophy of "learning by doing" and "learning by experimenting" characterized by higher levels of activities based on comprehension, application, analysis, synthesis, and evaluation of experience has shown that, in its relaxed and stimulating atmosphere, students are generally more motivated to actively commit themselves to the control design and its verification.

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