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New Thermo-Optical Plants for Laboratory Experiments

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Abstract: This paper explains motivation and gives a brief development history of a laboratory model of thermo-optical plant. Then it continues with a short description of linear and nonlinear identification and control experiments that may be carried out with the recently innovated model directly in a classroom from the Matlab/Simulink environment, or remotely via Internet.

Keywords: Thermal plant, optical plant, modeling, identification, PID control, constrained control, disturbance observer, dead time compensator, remote laboratory, Arduino

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1. INTRODUCTION

In the last two decades one may see a significant shift in control education paradigm that closely correlates with development of computers, computer networks, information and communication technologies. Briefly, it may be characterized as a shift from (pure) theoretical education to a more practically oriented ”learning by doing”, ”learning by experimenting”, or ”learning by discovering”. These all are features of the ”flexible learning revolution” coming together with a revolution in the field of Information and communication technologies (ICTs). This movement comes frequently as a bottom-up initiative, but, it is also (at least formally) underpinned by documents accepted by the top world political gremia as Unesco (Allen et al., 2002). Of course, one can discuss the degree of fulfillment of different action plans and meaningfulness of the accepted measures, as e.g. those proclaimed in European-Council (1995) two decades ago, or those accepted recently by the European Commission that gives for member states 6 priorities and one of them is Scale up the use of ICT-supported learning and access to high quality OER and Opening up Education (European-Commission, 2012). Many aspects of this movement might seem firstly to be a question just for the distance teaching universities. However, the recent development in the MOOCs area shows its global character. 12 top universities leaded by the elite academic institutions, as Harvard and MIT, supported by the not-for-profit (and now opened) MOOC platform edX, offer open courses, supporting textbooks and many other materials free of charge. All these global learning environment and methodology issues (as e.g. those discussed in Downes (2008-2011), together with request on increasing numbers of university students and improving college retention rates, marketing issues requiring to offer some courses free and open, etc.) indicate that a university system requires a vision and a lot of innovation and robustness to survive.

2. GENERAL REQUIREMENTS ON PLANT MODELS FOR EDUCATION

To be more specific, today in control education each success is conditioned by acquisition of an ”authentic” knowledge and skills related to ”authentic” control tasks (Allen et al., 2002). The idea of quasi-authentic control tasks oriented our inspiration to looking for solutions that would enable active student’s approach . It means, we were constructing set of ”real” control tasks that would be dealt with students in different learning setting, individually, in teams, in classrooms, or remotely. When starting our initiative some decades ago, with respect to the financial aspects it was clear that the new solutions must differ from the existing ones: the plants available on the market were far from to be cheap, they required additional A/D and D/A converters and special software for the real time control. But, we needed to have a large number of ”low-cost” plants guaranteeing (Huba and Šimunek, 2007):

- clear physical visibility of the controlled dynamics,
- time constants within the range ms-minutes,
- safe manipulation and easy maintenance,
- reasonable price,
- availability of all electronics, sensors and actuators,
- connectivity to standard computers without special converter cards and special real-time software,
- approach via Internet,
- plants with different degree of control difficulty (linear/nonlinear, SISO/MIMO,etc.)
- plants offering broader spectrum of dynamics,
- smallest possible dimensions of such devices, which should be placed in a limited individual workspace available in standard computer labs (Fig. 1)

3. THERMO-OPTICAL PLANTS FOR EDUCATION

The first prototype of a thermal plant (Michalik, 1987) has been inspired by the textbook Oldenbourg and Sartorius (1944, 1951). It consisted of two fans (220V, 1500W) blowing air into a 150 cm long pipe with a possibility to locate pt100 temperature sensors at different positions. The fans have been controlled via triac power amplifiers

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Fig. 1. Automatic control course in a standard computer lab with thermo-optical plant models 2006

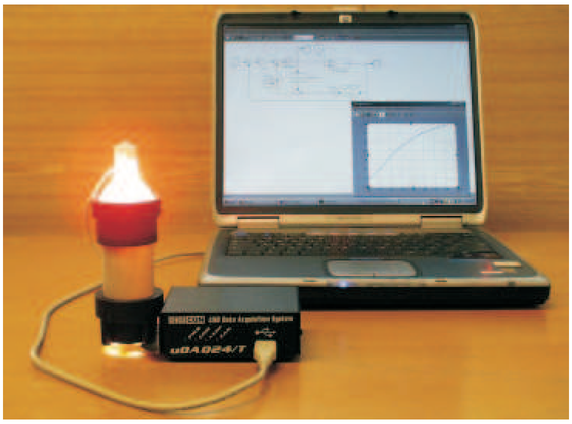


Fig. 2. Thermo-optical plant models 2005

and a HP-85 computer programmed in Basic: one as an actuator, the other one as a disturbance source. Due to the installed thermal power, work with this experiment was welcomed especially in cold winter days, when it helped to increase the room temperature. This, however, made it practically impossible to repeat experiments with the same results. When trying to evaluate with a higher precision, a transient never reached a steady-state. Besides of the restricted pedagogical use of single piece of equipment a measurement was also unpleasant due to the produced noise. But, the identification and controller design have been carried out fully digitally, what represented a significant progress with respect to identification and control of previously used thermostat controlled thermal plant, where many steps had to be done manually.

To enrich spectrum of available experiments (Žáková et al., 2000), several new prototypes of thermal plant controller already via PCs with converter cards directly from Matlab/Simulink environment have been built in the period 2000-2005. Starting with the 2005 model (Fig. 2) integrating firstly a thermal and an optical channel (Huba et al., 2006), by giving visual feedback in appropriate time scales, by simple communication, maintenance and connectivity to standard computers via USB port, by a broad spectrum of control tasks and by simple integration to Matlab/Simulink this plant represented a unique product practicable to all learning institutions. The most successful showed to be the model 2006 denoted as "uDAQ28/LT". Being produced in several slightly modified options (Huba, 2008) in 40 pieces, it attracted interest of a broader control community which may be documented by a relatively broad spectrum of different treated problems (see www.eas.sk for complete list of references and computer programmes). In the competition of the learning aids Pedagogical Forum'06 Bratislava this model received award of the Minister of Education of the Slovak Republic and at the elearning competitions of the international conferences Virtual University Bratislava 2009 and Iceta 2007 it significantly contributed to the rewards for the course Robust Constrained PID control.

The system offered three manipulated variables: the bulb voltage (the heat & light source), the fan voltage (the system cooling) and a light diode voltage (the second possible light source). There were eight measured outputs: the system temperature, the light intensity (both measured directly, or with apreliminary filtration), the light intensity derivative, the ambient temperature, the fan current and its speed of rotation. The filter and differentiation parameters could be set by the user (Jelenčiak et al., 2007). The measurement & communication system of the model 2006 used own microprocessor for the data processing and communication. It could be connected to standard computers via USB port without necessity of special converter cards and special real time control software. In this way, it significantly simplified the communication & control. By the developed drivers, in Matlab/Simulink, or in Scilab/Scicos the plant was represented as a single block. A possible extension module WebLab gave students a 24/7 access to the plant via Internet.

As many comparable solutions (see e.g. Sobota et al. (2013)), the latest thermo-optical system TOS 1A model 2013 uses standard microcomputer board Arduino. New microprocessor platforms as Arduino, BeagleBone, or Raspberry Pi are now being integrated into all experiments used for the control education support in our labs (Huba and Halás, 2011; Huba et al., 2013). Due to this new technology, the shortest sampling period for the plant/controller communication from Matlab/Simulink via the USB ports dropped from 50 to 15 ms. This may bring possibility of crucial improvements, e.g. in the disturbance observer based filtered PI control with higher order filters (Huba, 2013a).

4. WORK WITH THE THERMAL CHANNEL

The temperature control channel has been modified by using a reflector-free bulb and by omitting a plastic pipe tower. A power of the halogen bulb was reduced from 12V DC/20W to 5W. Similarly as for the previous model, due to the heat transfer by convection, conduction and radiation and the nonlinear character of the Stefan-Bolztmann law (Jelenčiak et al., 2007), the plant may be described by nonlinear differential equations and thus the input-to-output characteristic is typically nonlinear. A possible nonlinear model identification has been described in Jelenčiak et al. (2009). The nonlinear plant character causes that measuring step response for different operating points results again in a family of step responses with different shapes (Fig. 3). A linear plant approximation corresponds to a plant with fast and slow channels (Åström et al., 1998). Possible control algorithms leading to a significant performance improvements have been discussed e.g. in Ťapák et al. (2008); Huba et al. (2009). Since the time constants of the fast and slow models are significantly different, the most serious problem in this control design was related to a sufficiently precise plant model identifica-

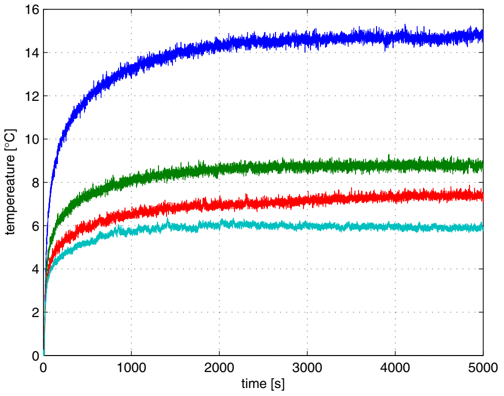


Fig. 3. Step responses of non-filtered temperature channel corresponding to the same step value and different initial conditions - bulb

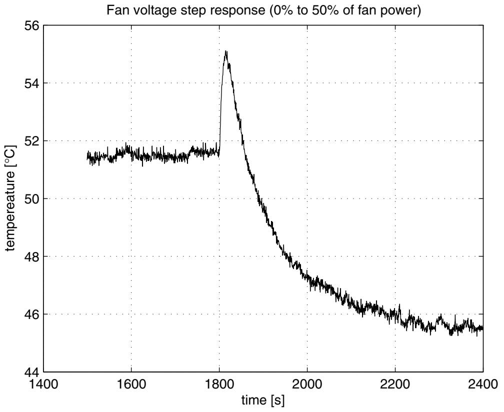


Fig. 4. Allpass dynamics corresponding to fan step response in temperature control

tion. The new construction allows a separate identification of the slow mode that considerably simplifies the overall identification problem. It is also possible to control just the fast mode what represents a strong advantage for the time limited tasks carried out during traditional classes.

Control of the 12V DC/0,6W fan of the 2006 model could be carried out just in a very limited scope. This feature has been optimized and now the fan speed may be controlled within a much broader range. Improved fan control enables to use it in a temperature control that typically has an all-pass character (Fig. 4).

5. WORK WITH THE OPTICAL CHANNEL

The light intensity control may be carried out either by using the halogen bulb (warm light source), or the light diode (cold light source) in role of an actuator. Thereby, the complementary light source may be used for generating disturbances. Also here, both input-to-output characteristic are typically nonlinear (Fig. 5).

Furthermore, one has to remember that a use of the bulb in role of the actuator contributes to increasing the system temperature and thus also to partial light signal drops (Fig. 6). A high speed of this channel allows to carry out in a short time numerous experiments and thus it

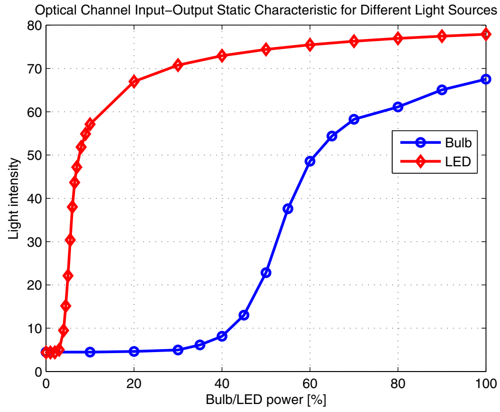


Fig. 5. Optical channel Input-Output static characteristic - bulb (red) and LED (blue)

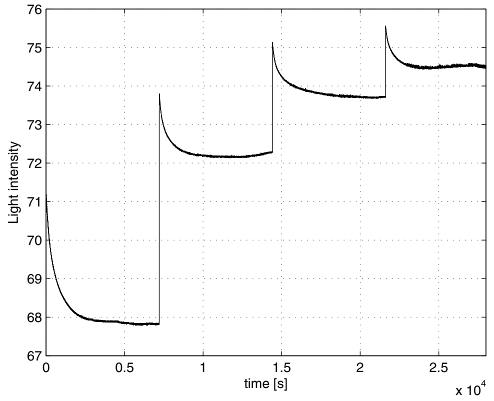


Fig. 6. Optical channel - bulb - details of the step responses show output decrease due to a temperature increase

is appropriate for demonstrating different control features in an introductory phase of control education typical by numerous mistakes.

6. EDUCATIONAL ASPECTS

The thermo optical plants are firstly used in an introductory course on Automatic control to show basic features of stability, performance and a plant identification. The core of their use relates to the course Constrained PID control described in Huba and Šimunek (2007). From the control point of view it is based on dynamical classes (DC) of control given by the number of pulses of a nearly time optimal control input. When interpreting the PID control as a control dealing with the dominant plants up to the 2nd order with a possible dead time, one needs to consider control of the DCs 0 (typical by a monotonic output setpoint step response achieved by a monotonic input), DC 1 (typical by a monotonic output setpoint step response achieved by a one-pulse input (Huba, 2013a)) and the dynamical class 2 (with a monotonic output setpoint step response achieved by a two-pulse input (Huba and Bélai, 2014)). This classification supports the newest course development that is dominant by integration of the controller tuning by the performance portrait method (Huba, 2013b,a; Huba and Soós, 2014).

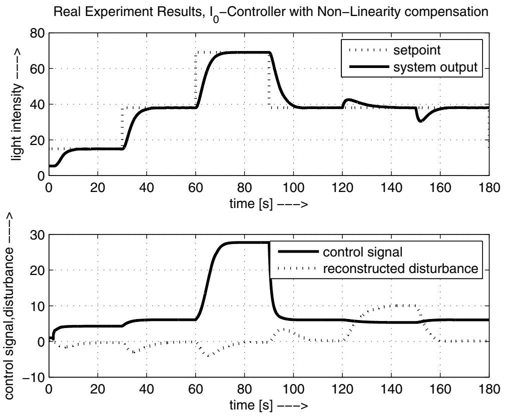


Fig. 7. I_0-controller, several upward and downward setpoint steps, followed by the disturbance downward and upward steps produced by the LED

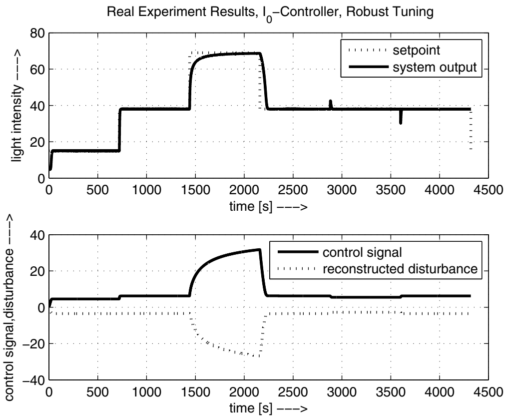


Fig. 8. I_0-controller, several upward and downward setpoint steps, followed by the disturbance downward and upward step produced by the LED

6.1 Dynamical Class Zero Experiments

As already mentioned, the light channel offers the fastest dynamics and thus it is suitable to begin with for a new user. Such experiments can be used for the tasks associated with a memoryless plant control combined a possible dead time or with a first order filter plus dead time, considering the dominant effect of a nonlinear input-output (I-O) characteristics. As an example the experiment result are shown achieved with an I_0-controller extended by a nonlinearity compensation using linear interpolation of the inverted I-O characteristics (Fig.7). Students learn to use look-up tables, or alternative polynomial approximations. To get monotonic setpoint step responses at the input and output corresponding to the DC 0 without a nonlinearity compensation, one may alternatively use a robust controller tuning (Huba, 2011) based on the maximal loop gain. Fig. 8 shows the real experiment results with such a tuning based on a maximal I-O characteristic slope. Due to the broad gain changes, robust tuning based on maximal loop gain leads mostly to overdamped transients. Nevertheless, monotonic shapes of transients are kept. The student task is to test properties of both approaches and to write conclusions discussing pros and cons of both approaches. Then, the task may be made more complex by using an output filter with longer time constant. Without a compensation, besides of an improved filtration this step leads to a prolonged transient responses. Students have to propose an active compensation of the filter dynamics by a lead-lag feedback term, or its equivalent in form of a linear PI controller with monotonic responses both at the plant input and its (non-filtered) output. This may yet be completed by an addition of a long dead time.

6.2 Dynamical Class 1 Experiments

From the point of view of the transients speed, the DC 1 controllers can be applied to a light channel as well. But, the students have to understand that a monotonic control of a filtered output represents mostly an artificial problem. Thus, when preferring a direct physical interpretation of the solved tasks, and since it might be boring for students to deal just with one plant channel, still there exist also other options. Many times the students consider the temperature channel and its dynamics to be more easy to understand. This makes it less abstract for them than the artificial problem of the filtered light intensity control. But, from the step responses of the temperature channel (Fig. 3) one can see that it takes approximately two hours to settle for the system output. Therefore, it is recommended to deal with this channel just after mastering the corresponding controllers designed for the light channel. Furthermore, a faster identification method has to be used, offered e.g. by a relay experiment (for a simple integrator plus dead time model) or some other closed loop identification method. The temperature channel has few more interesting features. One can see the step responses in Fig. 3 that deviates from typical exponentials of the first order plants. The reason is the two dominant modes of heat transfer in the plant: radiation - the bulb heats the sensor directly by radiation, conduction - the heat conduction via the plant body. These two modes run in parallel. If each of them would be approximated by the first order model, one would get the second order model with relative degree one (Ťapák et al., 2008). The model corresponding to radiation has approximately ten times lower time constant than the conduction mode's. Fig. 9 shows the temperature control, using PI-controller. Due to the large difference of the system time constants, in the following example there was only the fast time constant considered for the controller tuning. One can see the setpoint was reached in approximately 400 seconds, but the control signal, the bulb power, kept decreasing for more than one hour to compensate the zero dynamics of the plant.

6.3 Dynamical Class Two Experiments

A physically transparent tasks of the DC 2 may, for example, be achieved by putting an additional constraint on the admissible speed of control signal changes. This may be respected by introducing an additional integrator at the controller input. Its input constraint than determines speed of control signal changes. However, in designing the controller one has to respect also constraints put on the integrator output that correspond to the given control amplitude constraints. Thus, for a negligible filter dynamics, one gets a loop with an approximately first order dynamics, or, when considering control of a filtered

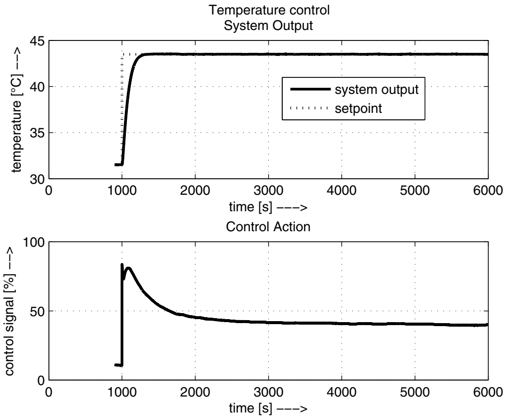


Fig. 9. PI-controller, Temperature control, setpoint step

optical output, or the thermal channel output, the control corresponds to the DC 2. Similar tasks may also be proposed by considering constraints put on the speed of the output changes.

6.4 *Time delayed control loops*

To deal with design of dead time compensators for time delayed systems, one may use the existing plant combined with an additional dead time introduced in Simulink. Indeed, it represents again an artificial problem, but effect of such a delay is very close to effect of time delays resulting e.g. from a communication, or from a computation. Thereby, a combination of the delay with a real plant offers many features of a quasi-authentic framework that is still characteristic by peculiarities of a real time control.

7. REMOTE EXPERIMENTS

Remote laboratories are nowadays an integral part of the educational system (Gomes and Bogosyan, 2009). In engineering education a student's stay in a laboratory has significant influence to the knowledge and skills the student can acquire. Remote laboratories represent a possible extension of classical laboratories to be open for students 24 hours per day. Therefore it is always desirable to introduce new laboratory experiments with the support of remote laboratories. The presented thermo-optical plant is equipped with the software module based exclusively on Matlab/Simulink capabilities that fulfills the task of a remote laboratory. Students and teachers in control education area are familiar with Matlab/Simulink that can enable them to build or modify a simple remote laboratory very quickly. The thermo-optical remote laboratory module uses client server architecture. Communication between the client and the server can be split into two independent channels (Fig. 10). Command channel is realized by a Matlab script that uses UDP objects from the Instruments Control Toolbox Library and serves for exchange of commands controlling the state of a remote experiment. In the Simulink client block diagram (Fig. 11) it is represented by control buttons placed in the upper part. Before running the experiment several parameters can be set (Fig. 12). Signal channel enables to exchange control signals and measurement data in both directions. It is realized by Simulink blocks UDP Send, UDP Receive and Pack (Fig. 11, 13). The outputs of the remote experiment can be seen continuously during the experiment using a Simulink Scope block (Fig. 14) or after the experiment has finished by standard Matlab plot command. The designed remote laboratory application is simple and flexible and can be easily modified. Of course there are also some limitations. At this time the client computer must use a public IP address as a result of UDP Send block usage on the server side. The next versions that are in progress will improve also several other features.

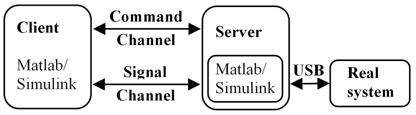


Fig. 10. Command and signal channels for commands and data exchange between the client and the server

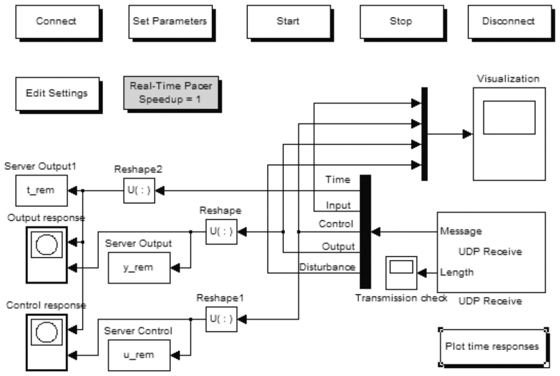
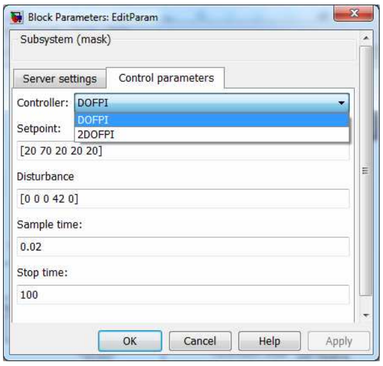


Fig. 11. Client application for thermo-optical remote laboratory build in Matlab/Simulink


Block Parameters: EditParam

Subsystem (mask)

Controller: DOFPI

Setpoint:
[20 70 20 20 20]

Disturbance
[0 0 0 42 0]

Sample time:
0.02

Stop time:
100

Fig. 12. Parameters of client application to be set before the experiment starts

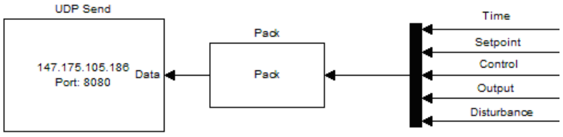


Fig. 13. Extension of the control block diagram of the server application responsible for continuously sending the signal data to the client side

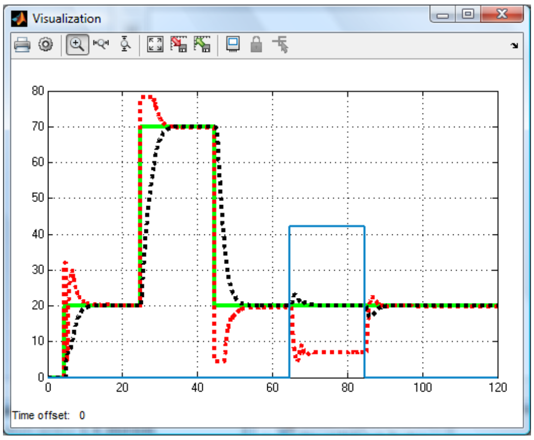


Fig. 14. Standard Simulink Scope block called Visualization plots process variable time responses during the running experiment online - green(setpoint), black (system output), red (control signal), blue (disturbance - LED power)

8. CONCLUSION

The developed teachware allows to start with a simple linear I, P and PI control and to continue to more advanced problems of a dynamical feedforward, constrained control, control of loops with a long dead time, etc. to TITO and MIMO problems with interactions among the optical and thermal channels. The available user guide contains already more than 40 different tasks from three different dynamical classes. Further problems may be shared by the still growing user community. The development continues with the TOS 1B 2014 model built on the BeagleBone boards devoted for remote labs and with construction, or reconstruction of other experiments.

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