

WEB-BASED CONTROL DESIGN ENVIRONMENT FOR DISTRIBUTED PARAMETER SYSTEMS CONTROL EDUCATION

G. Hulkó, C. Belavý, Š. Cibiri, J. Szuda

*University Center for Control of Distributed Parameter Systems
Department of Automation and Measurement, Faculty of Mechanical Engineering
Slovak University of Technology, Nám. Slobody 17, 812 31 Bratislava
Slovak Republic. E-mail: gabriel.hulko@stuba.sk*

Abstract: In the paper a web-based control design environment for distributed parameter systems control education is presented. It is arranged on www.dpscontrol.sk and includes: full downloadable demo version of Distributed Parameter Systems Blockset for MATLAB & Simulink with Show, Demos and DPS Wizard – third-party MathWorks product; web Service for support control solutions via internet and internet monograph Modeling, Control and Design of Distributed Parameter Systems with Demonstrations in MATLAB. Some possibilities of this environment are indicated by control of complex shape 3D metal body heating - modeled by numerical structures of finite element method.
Copyright © 2005 IFAC

Keywords: Control education; internet; distributed parameter systems; lumped-input/distributed-output systems; time/space decomposition of dynamics and control synthesis; distributed parameter PID, algebraic, state space, robust control; web based control design environment; finite element method.

1. INTRODUCTION

Explosive development of information technologies supports further wide-ranging distribution of diverse methods and software products for 3D numerical dynamical analysis of real systems as distributed parameter systems (DPS) in any field of technical practice. Nowadays, these sophisticated dynamical analysis methods and tools are enjoying a boom... a new discipline emerges in this sphere of applications – computational science and engineering. At present, practically every student of technical, or natural-scientific university courses becomes familiar with numerical methods of dynamical analysis. They come into contact with specialized software products as: ANSYS, FEMLAB, FLUENT, MODFLOW, PM-SYSTEMS, STAR-CD,... Ten thousands of sold licenses of these software products indicate massive interest of the

engineering practice about study of dynamical characteristics in time/space dependency. As a matter of fact, it means massive interest about DPS. However, nobody is explicitly talking about DPS. Therefore, the control education should have to react to this new important trend in engineering disciplines and to offer flexible methods of modeling, control and design of DPS for university education as well as engineering community. To ensure wide availability, a control design environment: **Distributed Parameter Systems** was drawn up on the web site www.dpscontrol.sk. In the paper, first fundamentals of the engineering approach to the control of DPS will be presented: distributed-interface/distributed-output systems (DDS), lumped-interface/distributed-output systems (LDS), decomposition of dynamics of controlled systems to time and space components and decomposition of control synthesis to time and space tasks. Further, particular sections of web-based

control design environment **Distributed Parameter Systems** will be described: internet monograph, Distributed Parameter Systems Blockset for MATLAB & Simulink – third-party MathWorks product and the Interactive Control, resp. internet Service in frame of LDScontrol – Control of Dynamical Systems Given on Complex Definition Domains.

2. DPS - DDS - LDS

In general, DPS are systems whose state or output variables, $X(x,y,z,t)/Y(x,y,z,t)$ are distributed variables or fields of variables, where (x, y, z) is a vector in 3D. In control theory, these systems are frequently considered as systems whose dynamics is described by partial differential equations (PDE), Butkovskij (1965), Lions (1971), Wang (1964). In the input-output relation, PDE define distributed-input/distributed-output systems (DDS) between distributed input $U(x,y,z,t)$ and distributed output variables $Y(x,y,z,t)$ at initial and boundary conditions given, see Fig. 1.



Fig. 1. Distributed-input/distributed-output system

Distributed systems frequently are found in the engineering practice as LDS, see Fig. 2, having the common structure according to Fig. 3. Here, the DDS block is obtained as a special case of LDS one.



Fig. 2. Lumped-input/distributed-output system $\{U_i(t)\}_{i=1,n}$ - lumped input variables, $Y(x,y,z,t)$ - distributed output variable

Dynamics of LDS is decomposed to time and space components. In the time dependency, there are for example discrete transfer functions:

$$\{SH_i(\bar{x}_i, z)\}_{i=1,n} \quad (1)$$

between i -th input variable and corresponding partial distributed output variable at point $\bar{x}_i = (x_i, y_i, z_i)$ for $i=1,n$.

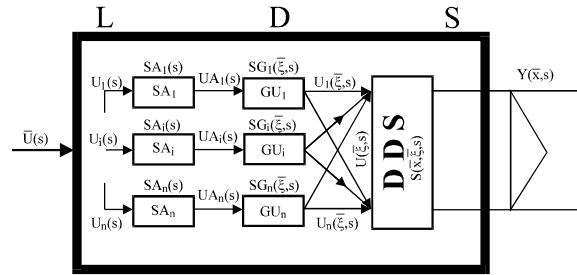


Fig. 3. Lumped-input/distributed-output system structure

$\{SA_i(s)\}_{i=1,n}$ - transfer functions of actuating gears of lumped variables $\{SA_i\}_{i=1,n}$; $\{SG_i(\bar{\xi}, s)\}_{i=1,n}$ - transfer functions of generators of distributed input variables $\{GU_i\}_{i=1,n}$; $S(\bar{x}, \bar{\xi}, s)$ - transfer function of distributed-input/distributed-output system; where $\bar{x}, \bar{\xi}$ - are vectors in 3D.

In the space dependency there are e. g. reduced transient step responses in steady-state:

$$\{\neq HR_i(\bar{x}, \infty)\}_{i=1,n} \quad (2)$$

3. DISTRIBUTED PARAMETER SYSTEMS OF CONTROL

Decomposition of dynamics enables also to decompose the control synthesis to time and space control tasks in distributed parameter control loop, see Fig. 4.

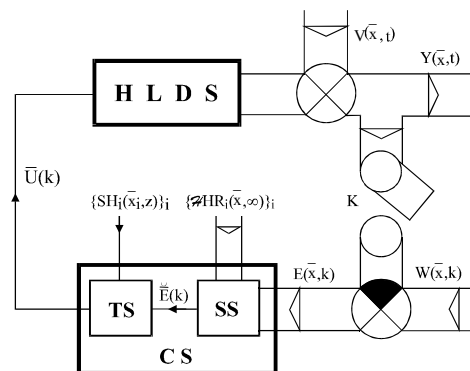


Fig. 4. Distributed parameter discrete feedback control loop at unit sampling period

HLDS - LDS with zero-order holds $\{H_i\}_i$ on the input, CS - control synthesis, TS - control synthesis in time domain, SS - control synthesis in space domain, K - time/space sampling, $Y(\bar{x}, t)$ - distributed controlled variable, $W(\bar{x}, k)$ - control variable, $V(\bar{x}, t)$ - disturbance variable, $E(\bar{x}, k)$ - control error

In the block SS, approximation of distributed control

error $E(\bar{x}, k)$, on the set of reduced steady-state distributed step responses $\{HR_i(\bar{x}, \infty)\}_i$, is solved. As the solution of approximation problem, lumped control error vector $\bar{E}(k)$ enters into the block TS, where vector of control variables $\bar{U}(k)$ is generated. The controllers, $\{R_i(z)\}_i$, Fig. 5, are tuned in single-parameter control loops $\{SH_i(\bar{x}_i, z), R_i(z)\}_i$, according to single components of the time part of the controlled distributed parameter system dynamics $\{SH_i(\bar{x}_i, z)\}_{i=1,n}$, see Fig. 6.

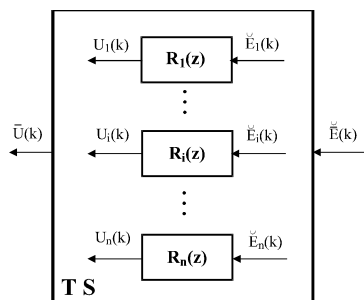


Fig. 5. Time synthesis block

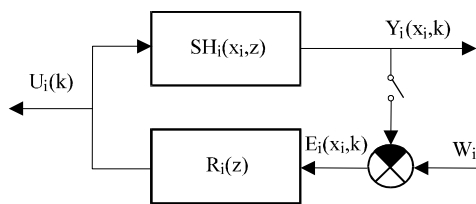


Fig. 6. i -th one-parameter control loop

On this principle, the distributed parameter control synthesis at PID, algebraic, state, robust as well as adaptive or intelligent control is decomposed into the time and space tasks, Hulkó (1998 - 2003).

4. WEB-BASED CONTROL DESIGN ENVIRONMENT

The web-based control design environment: **Distributed Parameter Systems** on the web site www.dpscontrol.sk offers both, methodical and software support for education and solution of engineering tasks as well as possibilities of interactive formulation and solution of model tasks of distributed parameter systems control via the internet. It is arranged on www.dpscontrol.sk and includes: a full downloadable demo version of Distributed Parameter Systems Blockset for MATLAB & Simulink – third-party MathWorks product, web Service for support distributed parameter control solutions via internet, in frame of LDScontrol – Control of Dynamical Systems Given on Complex

Definition Domains and internet version of the monograph Hulkó et. al. (1998).

4.1. Internet version of the monograph

The monograph Hulkó G. et. al.: Modeling, Control and Design of Distributed Parameter Systems with Demonstrations in MATLAB, Publishing House STU, Bratislava, 1998 is devoted to engineering methods of modeling, control and design of DPS based on lumped-input/distributed-output systems with set of MATLAB M-files DPSTOOL, bounded on disc in the book. This monograph is listed on the web side of MathWorks among MATLAB based books and presented among the top publications in internationale databases in the area of distributed parameter systems. Due to limited number of copies printed, the monograph was quickly sold out. For persevering interest of professional community, the electronic version has been drawn up. In the extensive ninth chapter demonstrations are presented based on analytical and numerical models of distributed parameter systems as well as models given by experimentally obtained distributed dynamic characteristics.

4.2. DPS Blockset for MATLAB & Simulink – third-party MathWorks product

The DPS Blockset is a blockset for use with MATLAB & Simulink for distributed parameter systems and their applications in modeling, control and design of dynamical systems given on complex 3D domains of definition, see Fig. 7.

The blockset features:

- Engineering methods for DPS modeling, control and design
- DPS models based on lumped-input/distributed-output systems, time/space analysis, synthesis and design tools
- Distributed parameter PID, algebraic, state space and robust control schemes
- DPS Wizard demonstrates in step-by-step operation distributed parameter control loops arrangement and setting procedures
- Suite of blocks and schemes for DPS control practically in any field of technical practice
- Interactive Control Service for support DPS control solutions via the internet

The block **HLDS** models controlled distributed parameter systems as lumped-input/distributed-output systems with zero-order hold units. The **DPS Control Synthesis** provides feedback to distributed parameter controlled systems in control loops with blocks for **PID, algebraic, state space and robust** control. The block **DPS Input** generates distributed quantities which can be used as distributed control variables or

distributed disturbances, etc. **DPS Display** presents distributed quantities with many options including export to AVI files. The block **DPS Space Synthesis** performs space synthesis as an approximation problem. The block **Tutorial** presents methodological framework for formulation and solution of distributed parameter systems of control. The block **Show** contains motivation examples: Control of temperature field of 3D metal body, Control of 3D beam of „smart“ structure, Adaptive control of glass furnace and Groundwater remediation control. The block **Demos** contains examples oriented to methodology of modeling and control synthesis. The **DPS Wizard** in step-by-step operation, by means of five model examples on 1D-3D with default parameters, gives a guide for arrangement and setting distributed parameter control loops. Now, some possibilities, which the DPS Blockset offers by control of metal body heating will be indicated, Fig. 8.

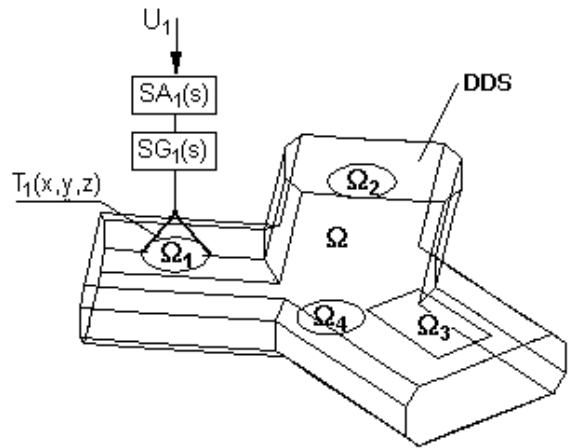


Fig. 8. Heating of metal body of complex shape $\{SA_i(s)\}_i$ - actuating members with lumped input variables, $\{SG_i(s)\}_i$ - generators of distributed input variables, $\{T_i(x,y,z)\}_i$ - shaping units in space domain on $\{\Omega_i\}_i$, DDS - distributed-input/distributed-output system on the Ω , $\{U_i\}_i$ - lumped input quantities

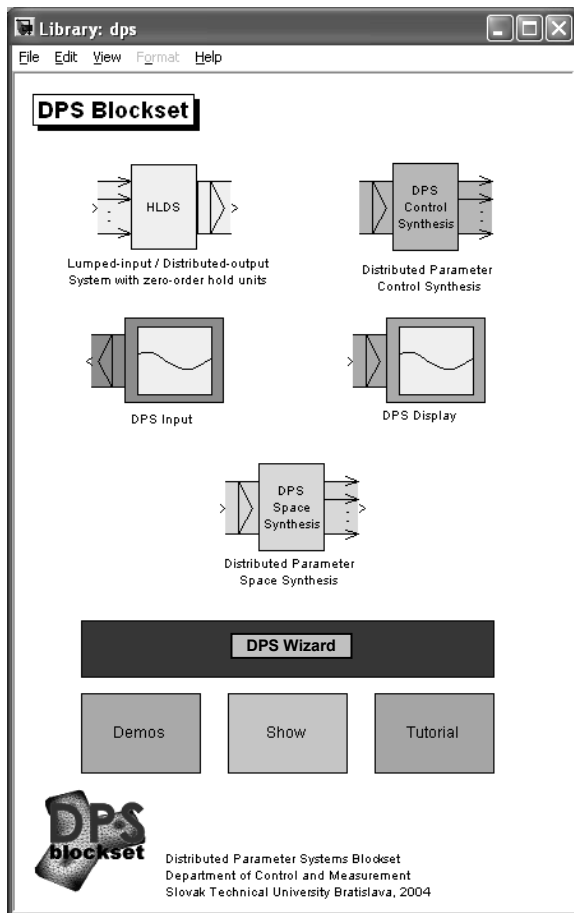


Fig. 7. DPS Blockset for MATLAB & Simulink

The dynamical model of metal body heating is given by numerical structures based on finite element method in FEMLAB. By means of blocks of the DPS Blockset a distributed parameter control loop is arranged, Fig. 9.

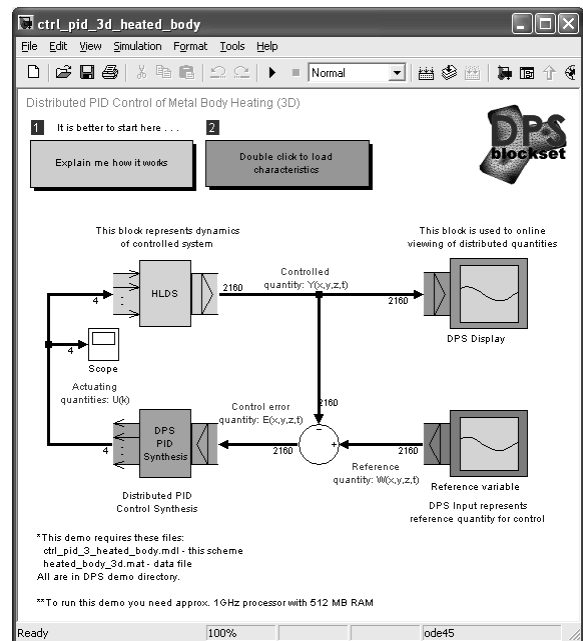


Fig. 9. Distributed parameter control loop

Distributed quantity is represented by temperatures computed at node points of the numerical net. In this case it means 2160-element vector at node points and values between node points are computed by spline functions. Control process simulation results are in Fig. 10.

4.3 Interactive Control

Internet service **Interactive Control** or **Service of LDScontrol** - Control of Dynamical Systems Given on Complex Definition Domains offers flexible

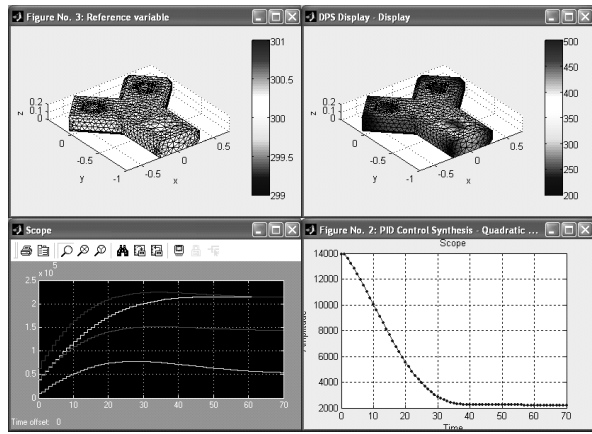


Fig 10. Process of control

a/ $W(x,y,z,\infty)$ - distributed reference quantity; b/ $Y(x,y,z,t)$ - distributed controlled quantity; c/ $\{U_i(t)\}_i$ - actuating variables; d/ $E(t)$ - quadratic norm of distributed control error $E(x,y,z,t)$

possibilities for formulation and solution of model control problems via the internet. Procedure of formulation and solution will be demonstrated by example presented above as heating of complex shape metal body. Metal body in the shape of Ω is heated as a linear system by heating elements $\{G_i\}_i$, $i=1,2,3$ which act on subdomains $\{\Omega_i\}_i$, $i=1,2,3$.

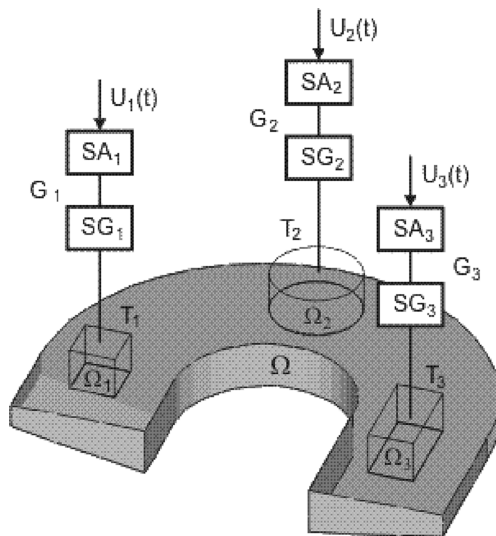


Fig. 11. Heating of 3D metal body

Now, let us assume that in blocks modeling heating elements dynamics next relations hold: $\{SA_i(s)=1\}_i$, $\{SG_i(s)=1\}_i$ - similarly at shaping units in space domain: $\{T_i(x,y,z)=1\}_i$. Then distributed input quantities on $\{\Omega_i\}_i$ are constant and are given by $\{U_i(t)\}_i$. Let us denote these quantities as $\{U_{\Omega_i}(t)\}_i$. Fig. 12. The control task should be to transfer stable temperature field from the zero initial steady-state: $W(x,y,z,0)=0$ °C to a new steady-state at $t \rightarrow \infty$: $W(x,y,z,\infty)=\text{Const.}$ °C by means of distributed

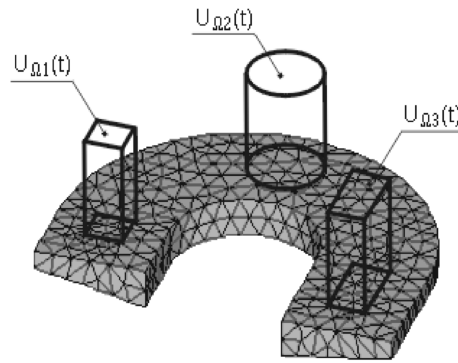


Fig. 12. Distributed input quantities at model problem: when $\{SA_i(s)=1\}_i$, $\{SG_i(s)=1\}_i$ and $\{T_i(x,y,z)=1\}_i$

input quantities $\{U_{\Omega_i}(t)\}_i$. The goal of the control synthesis is to generate actuating quantities of heating elements $\{G_i\}_i$: $\{U_i(t)\}_i$ such that control error quadratic norm $E(t)$ of $E(x,y,z,t)$ between reference quantity $W(x,y,z,\infty)$ and controlled quantity $Y(x,y,z,t)$ at $t \rightarrow \infty$ will obtain minimal value. By this way, every person interested can formulate an elementary model control problem in his own discipline. Further, for simplicity, procedure of formulation and solution will be arranged in some steps:

1. Localization of input influences. On the definition domain of controlled system Ω suitable sub-domains $\{\Omega_i\}_i$ are chosen for the inlets of distributed control inputs.

2. Choice of shaping units. For simplicity, let shaping units in space domain have constant forms with unity amplitudes $\{T_i(x,y,z)=1\}_i$. In general, $T_i(x,y,z)$ for $i=1,n$ are given with values of $T_i(x,y,z)$ at chosen points and by spline functions on Ω_i .

3. Choice of dynamical characteristics of blocks SA, SG and inputs U. For simplicity, let $\{SA_i(s)=1\}_i$, $\{SG_i(s)=1\}_i$ and amplitudes of inputs according to operation regime chosen. In general, $\{SA_i\}_i$ and $\{SG_i\}_i$ for $i=1,n$ are given with transfer functions.

4. Definition of the mesh. The appropriate meshing, by the numerical method, is used on Ω at $\{\Omega_i\}_i$, given. Then geometry model is defined as matrix \mathbf{M} of coordinates of mesh nodes - $\underline{nn} \times 3$ for 3D models, or $\underline{nn} \times 2$ for 2D models, where \underline{nn} is the number of computational nodes and matrix \mathbf{E} of serial numbers of vertexes of basic geometry elements in counterclockwise direction - matrix of dimension $\underline{ne} \times 3$, $\underline{ne} \times 4$ or $\underline{ne} \times 8$, where \underline{ne} is the number of controlled system geometry model basic elements: triangles, tetragons in 2D and tetrahedrons, resp. cubes or prisms in 3D.

5. Calculation of system responses. At points of mesh on sub-domain Ω_i , constant input quantities U_i are introduced. In other points of Ω input quantities are equal to zero. Then the response of dynamical system from the zero initial steady-state - the step response matrix H_i (H_i is system response by input influences actuated only on Ω_i , while input influences on other sub-domains are equal to zero) is calculated.

6. Choice of reference quantity. For simplicity, let us assume a constant value of reference quantity for the new steady-state at $t \rightarrow \infty$: $W(x,y,z,\infty) = \text{Const.}$ for control from the zero initial steady-state. *In general, $W(x,y,z,k)$ is given for single points of the mesh as a discrete time function at the sampling interval chosen. Distributed disturbances $V(x,y,z,t)$ are given similarly.*

These results of formulation procedure

» geometry model - M, E

» transient responses - matrices $\{H_i\}_i, \{U_i\}_i, T$

» reference quantity - $W(x,y,z,\infty)$

are submitted via internet to specified FTP server.

7. Control synthesis. Control synthesis in the space domain is solved as an approximation problem and in the time domain by PSD controllers. *In general, for control synthesis in the time direction there are various algebraic, state-space, robust control... synthesis methods available.*

Finally, the process control results are transferred to the interested person via the FTP, like in Fig. 10.

5. CONCLUSION

Engineering methods and tools presented for modeling and control of DPS, particular blocks of DPS Blockset for MATLAB & Simulink and the internet Service procedure show that dynamics of DPS is decomposed into time and space components. Then, problems of identification and control synthesis are decomposed into time and space tasks also. Meanwhile, time problems are solved as lumped parameter systems identification and control synthesis tasks and space problems by approximation and optimization methods. In general, it can be stated that the engineering approach presented here to DPS control leans on standard results of lumped parameter systems control, and approximation, resp. optimization methods. Consequently, education in this discipline don't impose any qualitative new requirements on students. In the frame of MSc. courses "Automatic Control and Information Engineering" and "Mechatronics" at the Slovak University of Technology in Bratislava in 5-th class subjects "Control of Distributed Parameter Systems" (2-1 hours per week) and "Control of Continuum Mechanical Systems" (2-1 hours per week) are lecturing. Prior to this, in lower classes, students have subjects "Control Theory I. - III.", "Computational

Mechanics", resp. "Numerical analysis of machines and processes". Meanwhile, students exploit MATLAB, Simulink and some of software products: ANSYS, FEMLAB or FLUENT for numerical dynamical analysis of machines and processes. At the education control design environment **Distributed Parameter Systems** from web site www.dpscontrol.sk is used. Students master these subjects without any problems...

ACKNOWLEDGEMENT

This work has been carried out under the financial support of the Slovak Scientific Grant Agency VEGA to project „Control of Systems Given by Numerical Structures on Complex Definition Domains with Demonstrations via Internet“ (grant 1/9278/02) and the Slovak State Agency for Science and Technology to project „Modeling, Control and Simulation of Distributed Production Systems“ (grant APVT-51-011602).

REFERENCES

- Butkovskij, A. G. (1965). *Optimal control of distributed parameter systems*. Nauka, Moscow. (in Russian)
- Hulkó, G. et al. (1998). *Modeling, Control and Design of Distributed Parameter Systems with Demonstrations in MATLAB*. Publishing House of STU, Bratislava.
- Hulkó, G. et al. (2002). *Control of Dynamical Systems Given on Complex Definition Domains* - www.dpscontrol.sk. The 3rd Int. Conference on VIRTUAL UNIVERSITY, Bratislava.
- Hulkó, G., Belavý, C. (2003). *PID control of distributed parameter systems*. The IFAC Conference on CONTROL SYSTEMS DESIGN '03, Bratislava.
- Hulkó, G. et al. (2003). *Interactive Web-based Learning Service for Control of Dynamical Systems Given on Complex Definition Domains*. The 6-th IFAC Symposium on Advances in Control Education. Oulu, Finland
- Lions, J. L. (1971). *Optimal control of systems governed by partial differential equations*. Springer-Verlag.
- Wang, P.K.C. (1964). *Control of distributed parameter systems*. In: *Advances in Control Systems: Theory and Applications*, 1, Academic Press.