IMPLEMENTATION OF 7 DOF ROBOTIC SYSTEM FOR FAST UNSTABLE PROCESSES

Lubos Spacek and Jiri Vojtesek
Tomas Bata University in Zlin
Faculty of Applied Informatics
Nad Stranemi 4511, 760 05 Zlin, Czech Republic
E-mail: {spacek,vojtesek}@utb.cz

KEYWORDS

YuMi, robotics, LQ polynomial control, 7DoF, Ball & Plate.

ABSTRACT

The industrial robotics is a fast growing area which reaches beyond automotive and large companies. More special tasks are required from robots than before, some of which require dynamic reactions from the robot based on external sensors. This paper presents solution for controlling of unstable processes using collaborative robotic manipulator ABB YuMi. The Ball & Plate model serves as an example of the relatively fast and unstable system. The linear quadratic (LQ) polynomial 2DoF controller is used because of its easy implementation to the robot's code and reliable behavior. Working system is presented and solutions are provided to improve the quality and overall stability of the solution.

INTRODUCTION

Industrial robots are now at their peak in automation with numerous applications requiring flexibility and fast implementation. There are basic applications such as pick and place, but also more complex ones where robots use external sensors to alter their paths dynamically in real time, for example force controllers or special paint atomizers. This paper deals with the industrial robot controlling an unstable process and the Ball & Plate model was chosen to represent such system. There are many Ball & Plate solutions ranging from 2DoF plates (Jadlovska et al. 2009) to 6DoF Stewart platforms (Kassem et al. 2015), however all solutions rely on parallel structures. This paper presents solution with 7DoF connected in series to control the Ball & Plate model.

The linear quadratic (LQ) polynomial control solution (Bobal et al. 2005) is one of several approaches to controller design. This paper presents LQ control for 2DoF polynomial controller (Matusu and Prokop 2013), which is relatively reliable strategy able to control many different plants with easy implementation to the code of the robot and satisfying robustness against slight changes in system parameters. Spectral factorization (Sebek 2015) is used for minimization of LQ criterion which is fast method for this kind of problem. ABB IRB 14000 YuMi is a collaborative industrial robot that serves as a motion system in this paper. It has two manipulator arms with 7DoF each. This robot was chosen because of its two arms that can work together to achieve more tasks and thus can be used in the following research, however only one of its arms is used in this paper.

The paper is organized as follows. The first chapter describes the robot, Ball & Plate system and LQ controller separately in their own subsections. It presents the theory and basic parameters to introduce the overall concept. The second chapter shows identification of the model and subsequent control of the whole system on the real robot with presented results. The last chapter concludes the paper.

METHODS

7DoF Robotic System

Collaborative robots have safety standards that allow them to work side by side with human operator without additional protection such as cage (Fryman and Matthias 2012). This human-robot collaboration combines cognitive abilities of humans with precision, strength and endurance of robots (Thomas et al. 2016). Using collaborative robot in research is advantageous because humans can access the robot directly and make tests without worrying about their physical interaction with the robot. In case the robot hits an object (or a human), it stops without damaging accessories, itself and without hurting personnel around. This fact greatly reduces testing and implementation time. Standard robotic manipulators have 6 DoF (degrees of freedom) structure, which is sufficient enough to complete all given tasks. However dual-arm robots need an extra flexibility while reaching difficult-to-access positions and ensuring arms do not collide with each other at the same time.

ABB IRB14000 YuMi is industrial collaborative robot (Fig. 1) with two 7DoF manipulators, repeatability 0.02 mm and load capacity of 0.5 kg each (ABB 2019). This load capacity is quite low and the robot is best suited for assembly of small parts and electronics. The maximum speed of tool center point of the robot is 1500 mm/s (mainly because of payload limitation), which is faster than any other commercially available robot while maintaining all safety standards. This speed theoretically allows to control even relatively fast processes.

The robot can be completely simulated in RobotStudio environment by ABB. It also includes physics virtualization with gravity, friction and material properties already implemented. The virtualized robot directly simulates its real counterpart and the code can be eas-

Communications of the ECMS, Volume 33, Issue 1,
Proceedings, ©ECMS Mauro Iacono, Francesco Palmieri,
Marco Gribaudo, Massimo Ficco (Editors)
ISBN: 978-3-937436-65-4/978-3-937436-66-1(CD) ISSN 2522-2414

Fig. 1. Collaborative robot ABB IRB 14000 YuMi

ily shared between them. The robot balancing a ball on a plate in simulated environment is shown in Fig. 2.

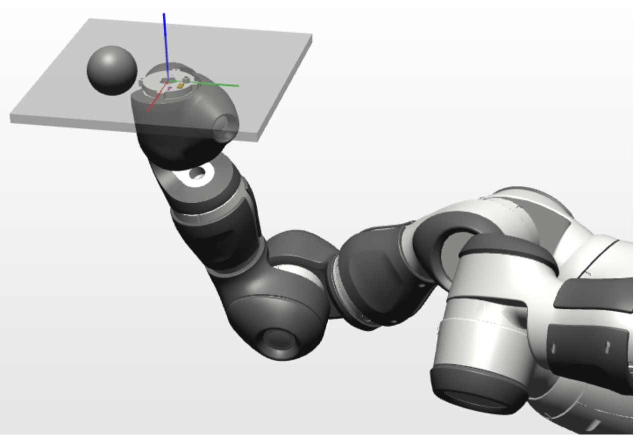

Fig. 2. Robot YuMi balancing a ball on a plate

Ball & Plate Model

Ball & Plate model is a classic example of a fast unstable process and will be inspected as a suitable representative of similar systems. It consists of a ball on a plate and the goal is to move the plate in order to control the position of the ball. The system has generally 2 inputs (angles of the plate) and 2 outputs (x-y position of the ball from the center of the plate) and has an unstable nature. Described system can be expressed by Euler-Lagrange equation of the second kind (Rumyantsev 1994) which leads to (1) and (2) for this specific system.

$$x\colon \left(m + \frac{I_b}{r^2}\right)\ddot{x} - m\left(\dot{\alpha}\dot{\beta}y + \dot{\alpha}^2 x\right) + mg\sin\alpha = 0 \quad (1)$$

$$y\colon \left(m + \frac{I_b}{r^2}\right)\ddot{y} - m\left(\dot{\alpha}\dot{\beta}x + \dot{\beta}^2 y\right) + mg\sin\beta = 0 \quad (2)$$

where x, y, $\ddot{x}$ and $\ddot{y}$ are x-y position coordinates of the ball and their corresponding second time derivatives, α, β, $\dot{\alpha}$ and $\dot{\beta}$ are angles of the plate and their corresponding first time derivatives and g, r, m and I_b are constants representing gravitational acceleration, radius, mass and the moment of inertia of the ball respectively. Note that angle α is responsible for changing the coordinate x and similarly the angle β changes the coordinate y. This model will not take slip between the ball and the plate into account and it is possible to simplify and linearize it around the center of the plate ($[x, y] = [0, 0]$). For further details see (Spacek 2017) with result being presented in (3) and (4).

$$x\colon \quad \ddot{x} = K_b\alpha \quad (3)$$

$$y\colon \quad \ddot{y} = K_b\beta \quad (4)$$

where K_b is constant dependent on the gravitational acceleration g and the hollowness of the ball. This simplified structure however does not consider dynamics of used actuators. It is obviously quite challenging to obtain a mathematical model of seven motors connected in series without knowing their parameters. This problem will be solved by experimental identification of the whole Ball & Plate system together with the manipulator.

The real Ball & Plate was constructed using a resistive touch screen to determine coordinates of the ball on the plate. The whole plate has dimensions 322x247 mm. Resistive touch screens are mostly made for displays which do not have square based sizes, but sides of the plate do not need to be equal for control purposes. Because the resistive touch technology needs a certain pressure to work properly a heavier ball had to be used. A steel bearing ball with 25 mm diameter was used, constructed from 100Cr6 steel, thus weighing about 64 g, which is enough for the resistive touchscreen to read the correct position of the ball.

Digital LQ Polynomial Control

The digital polynomial 2DoF control system is shown in Fig. 3, where $w(k)$ is reference value, $u(k)$ is controller output, $n(k)$ and $v(k)$ are disturbances and $y(k)$ is output of the plant. 2DoF controller consists of two parts - feed-forward part C_f and feed-back part C_b. The integration element ($\frac{1}{K(z^{-1})}$) of both parts is isolated to prevent them from reaching unnecessarily high values. $P(z^{-1})$, $Q(z^{-1})$, $R(z^{-1})$ are polynomials of these controllers and $A(z^{-1})$ and $B(z^{-1})$ are polynomials of the Ball & Plate system.

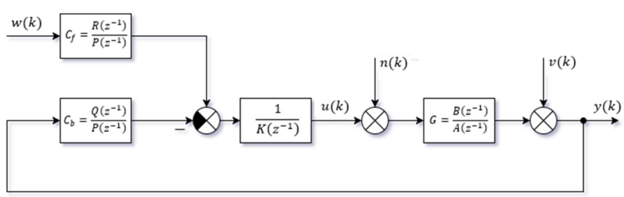

Fig. 3. Control scheme with implemented 2DoF controller

This type of controller provides relatively good results, it's implementation is reliable and fast. It has also remarkable robustness while maintaining control quality, much to the surprise of authors. The relation from

Fig. 3 between the reference value and the output of the system can be expressed by (5), where all disturbances are neglected and polynomial notations are omitted.

$$Y(z^{-1}) = \frac{BR}{AKP + BQ} W(z^{-1}) \tag{5}$$

The denominator of (5) forms a characteristic polynomial of the system $D(z^{-1})$. How to choose the correct degree of the characteristic polynomial is described in (Bobal et al. 2005). Generally the 2DoF polynomial controller has the structure shown in (6) and (7), where n_p and n_q are degrees of polynomials calculated using the degree of characteristic polynomial and the degree of system polynomials $A(z^{-1})$ and $B(z^{-1})$. The polynomial $R(z^{-1})$ will be a zero order polynomial for step change controller design (Bobal et al. 2005).

$$C_b(z^{-1}) = \frac{Q}{P} = \frac{\sum_{i=0}^{n_q} q_i z^{-i}}{1 + \sum_{i=1}^{n_p} p_i z^{-i}} \tag{6}$$

$$C_f(z^{-1}) = \frac{R}{P} = \frac{r_0}{1 + \sum_{i=1}^{n_P} p_i z^{-i}} \tag{7}$$

Poles of the characteristic polynomial are determined by minimization of LQ criterion in (8).

$$J = \sum_{k=0}^{\infty} \left\{ [e(k)]^2 + q_u [u(k)]^2 \right\} \tag{8}$$

where $e(k)$ is the error, $u(k)$ is controller output and q_u is penalization constant.
State-space description of the problem leads to solution of Riccati equation.The spectral factorization can be used for minimization of this criterion for input-output description of the system, more closely described in (Sebek 2015) and (Bobal et al. 2005). This technique allows authors to obtain the half of poles of optimal solution for the given system. The other half is chosen by authors to make the process more robust.

RESULTS

Identification

The identification is needed to obtain the model because it cannot be derived from mathematical model and without parameters of the manipulator. The experimental identification is thus the only option to determine the dynamics of the system and subsequently design the controller. The identification was made for both angles separately because the behavior of 7 motors connected in series is not expected to be symmetric as in most of Ball & Plate models. Step responses of the system were measured for 5-degree angle for all 4 plate inclinations ($\pm\alpha$,$\pm\beta$), averaged and identified for general structure of continuous-time transfer function in (9).

$$G(s) = \frac{K_b}{s^2 (Ts + 1)} \tag{9}$$

where K_b represents acceleration gain and T is time constant of the stable part of the system. This model is derived from (3) and (4), but with added first order transfer function approximating dynamics of the manipulator. Results are shown in Fig. 4, Fig. 5 and Equations (10) and (11).

$$G_x(s) = \frac{2.7150}{s^2 (0.9510s + 1)} \tag{10}$$

$$G_y(s) = \frac{2.7688}{s^2 (0.8367s + 1)} \tag{11}$$

Equations (10) and (11) are then discretized for sampling period 0.05 s and presented in the form shown in (12) with calculated coefficients b_i and a_i.

$$G(z^{-1}) = \frac{b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}} \tag{12}$$

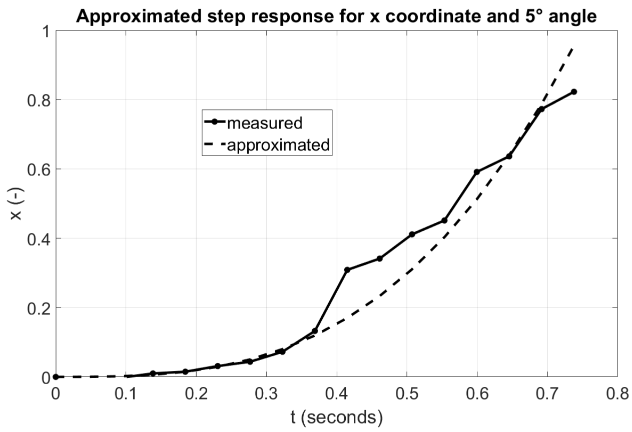

Fig. 4. Identification of the system for x coordinate

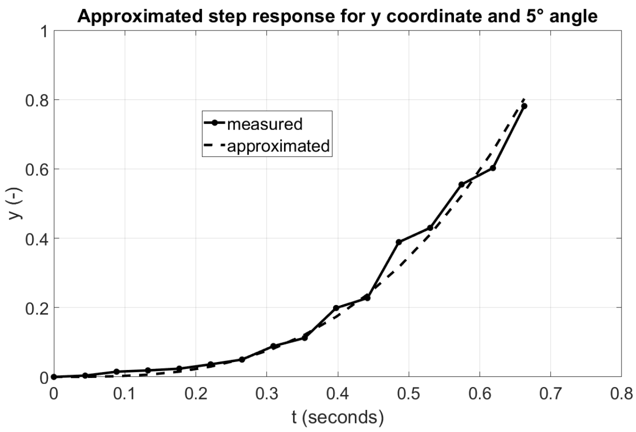

Fig. 5. Identification of the system for y coordinate

Control Results

The degree of the characteristic polynomial (denominator in (5)) can be obtained with the knowledge of degrees of polynomials of the system and coefficients of the controllers can be subsequently calculated. It should have 6th degree and thus the form shown in (13).

$$D(z^{-1}) = \sum_{i=0}^{6} d_i z^{-i} \tag{13}$$

Degrees of polynomials $P(z^{-1})$, $Q(z^{-1})$ and $R(z^{-1})$ can be obtained from the characteristic polynomial degree and are shown in (14) and (15).

$$C_b(z^{-1}) = \frac{Q}{P} = \frac{q_0 + q_1 z^{-1} + q_2 z^{-2} + q_3 z^{-3}}{1 + p_1 z^{-1} + p_2 z^{-2}} \quad (14)$$

$$C_f(z^{-1}) = \frac{R}{P} = \frac{r_0}{1 + p_1 z^{-1} + p_2 z^{-2}} \quad (15)$$

These equations can be rewritten to the form (16) that is easily implemented to basic micro-controllers or control units.

$$\begin{aligned} u_k = (1-p_1)u_{k-1} + (p_1 - p_2)u_{k-2} + p_2 u_{k-3} + \\ + r_0 w_k - q_0 y_k - q_1 y_{k-1} - q_2 y_{k-2} - q_3 y_{k-3} \end{aligned} \quad (16)$$

where u, w and y are signals described in Fig. 3 and p_i, q_i and r_0 are coefficients of controller calculated by methods described in LQ controller chapter and more closely in (Spacek et al. 2017).
Resulting measurements on the real system with the robot (Fig. 6) are shown in the following figures. Fig. 7 and Fig. 9 show the position of the ball and Fig. 8 and Fig. 10 show the angle of the plate for x and y coordinates respectively.

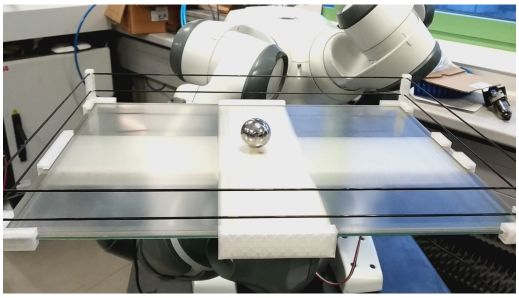

Fig. 6. Collaborative robot YuMi holding the Ball & Plate

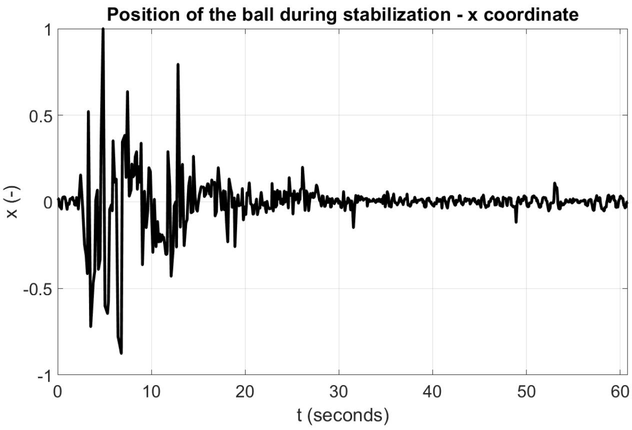

Fig. 7. Position of the ball in the x coordinate

Position values are normalized and angles of the plate are expressed in degrees. The ball was placed in the middle and random force was applied in the diagonal direction of the plate. The controller acted accordingly to its design and expectations. Because of internal software structure of the robot, it executed only approximately every 6th output from the controller. This changed the sampling period essentially from 0.05 s to almost 0.3 s, which is of course unacceptable (but hardly avoidable) behavior. On the bright side, this only supports the statement about robustness of the designed controller. There are several options to solve this problem for which further research is needed. One solution is the set of functions from ABB called Externally Guided Motion (ABB 2008) which provides several helpful tools. Another solution is to use ROS - Robot Operating System (Koubaa et al. 2018) which provides tools for bypassing the original system of the

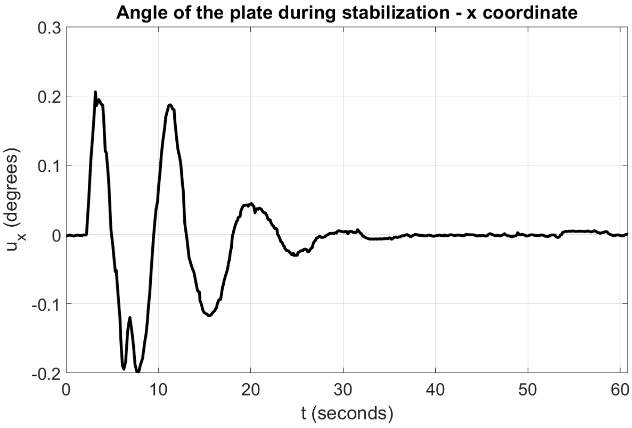

Fig. 8. Angle of the plate changing the x coordinate

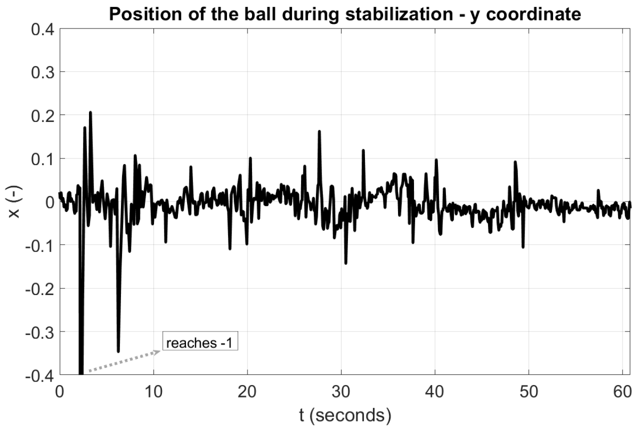

Fig. 9. Position of the ball in the y coordinate

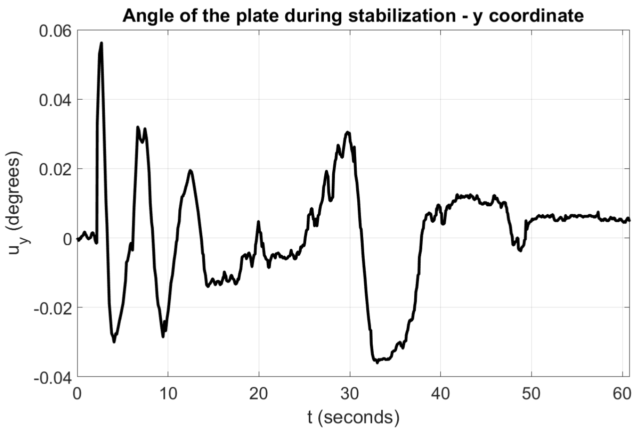

Fig. 10. Angle of the plate changing the y coordinate

robot and control its movements directly via ROS's framework.

DISCUSSION

It can be observed that the ball stabilized in the center of the plate roughly after 25 seconds (Fig. 8 clearly shows the force was applied after 3 s from the start of the measurement). This is a relatively long time for the stabilization which was mainly caused by the logic of the industrial robot itself. Industrial robots are designed to move from one position to another and these positions are often hard-coded in the code of the robot, which will not execute the next move instruction before the previous was reached. Industrial robots are simply not designed to dynamically respond to external factors (with the exception of safety protocols and their own control mechanism). The robot thus acts as a black box for the user. This problem can be solved by using special functions which ABB commonly calls External Guided Motion. These functions are however available only for 6-axis robots and more research is needed to use it for 7-axis ones. Another alternative is to aim the research to Robot Operating System, which also provides tools to solve the current problem.

ACKNOWLEDGMENT

This article was created with support of the Ministry of Education of the Czech Republic under grant IGA reg. n. IGA/CebiaTech/2019/004.

REFERENCES

ABB; Application manual - Controller software IRC5, Externally Guided Motion 689-1, 2008, Document ID: 3HAC050798-001, pp.326–375.

ABB; YuMi IRB 14000 data sheet, 2019. Available from: `https://new.abb.com/products/robotics/industrial-robots/irb-14000-yumi`.

Bobal, V.; J. Bohm; J. Fessl; and J. Machacek. *Digital Self-tuning Controllers*. Springer-Verlag, London, 2005.

Fryman, J. and B. Matthias. "Safety of Industrial Robots: From Conventional to Collaborative Applications". *7th German Conference on Robotics*, ROBOTIK 2012, pp.1-5, May 2012

Jadlovska, A.; S. Jajcisin; and R. Lonscak. "Modelling and PID Control Design of Nonlinear Educational Model Ball & Plate". In *Proceedings of the 17th International Conference on Process Control 09*, 2009. Strbske Pleso, Slovakia, 475-483.

Kassem, A.; Haddad H. and Ch. Albitar. "Commparison Between Different Methods of Control of Ball and Plate System with 6DOF Stewart Platform". IFAC-PapersOnLine, 2015, pp. 47–52, DOI: 10.1016/j.ifacol.2015.09.158, ISSN 24058963.

Koubaa, A (Ed.); Robot operating system. New York, NY: Springer Berlin Heidelberg, 2018. ISBN 978-3-319-91589-0.

Matusu, R. and R. Prokop. Algebraic design of controllers for two-degree-of-freedom control structure. In International Journal of Mathematical Models and Methods in Applied Sciences, vol. 7, 630-637, 2013.

Rumyantsev, V. V.; "Lagrange equations (in mechanics)" in Encyclopaedia of Mathematics, vol. 10, 1994.

Sebek, M. "Spectral Factorization". In: Baillieul J., Samad T. (eds) Encyclopedia of Systems and Control. Springer, London, 2015.

Spacek, L.; Bobal, V.; and J. Vojtesek. "LQ Digital Control of Ball & Plate System". *31st European Conference on Modelling and Simulation ECMS 2017*, pp. 427–432. European Council for Modelling and Simulation, 2017.

Thomas, C.; B. Matthias; and B. Kuhlenktter. "HumanRobot Collaboration New Applications in Industrial Robotics". *International Conference in Competitive Manufacturing 2016*.

AUTHOR BIOGRAPHIES

LUBOS SPACEK studied at the Tomas Bata University in Zlin, Czech Republic, where he obtained his masters degree in Automatic Control and Informatics in 2016. He currently attends PhD study at the Department of Process Control, Faculty of Applied Informatics. His e-mail address is `lspacek@utb.cz`.

JIRI VOJTESEK was born in Zlin, Czech Republic in 1979. He studied at Tomas Bata University in Zlin, Czech Republic, where he received his M.Sc. degree in Automation and control in 2002. In 2007 he obtained Ph.D. degree in Technical cybernetics at Tomas Bata University in Zlin. In the year 2015 he became associate professor. He now works at the Department of Process Control, Faculty of Applied Informatics of the Tomas Bata University in Zlin, Czech Republic. His research interests are modeling and simulation of continuous-time chemical processes, polynomial methods, optimal, adaptive and nonlinear control. You can contact him on e-mail address `vojtesek@utb.cz`.