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A Survey of Decentralized Adaptive Control

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1. Introduction

Systems with multi inputs and multi outputs are in common controlled by centralized controllers, multivariable controllers or by a set of single input and single output controllers. The decentralized systems dominated in industry due to the following advantages: flexibility in operation, failure tolerance, simplified design and tuning (Garelli et al., 2006).

Decentralized control techniques can be found in a broad spectrum of applications ranging from robotics to civil engineering. Approaches to decentralized control design differ from each other in the assumptions – kind of interaction, the model of the system, the model of information exchange and the control design technique (Keviczky et al., 2006).

Bakule wrote the nice paper that reviews the past and present in the area of decentralized control (Bakule, 2008). The usefulness of decentralized control is provided in a very readable way. The paper includes the description of disjoint subsystems, overlapping subsystems, symmetric composite systems and decentralized networked control. One of the useful approaches to decentralized control problems was the parametrization (Date and Chow, 1993). This paper is extended by the work of Garelli et al. (Garelli et al., 2006) who focused on the limiting interactions in decentralized control of systems. During decentralized control might appear some problems at systems composed of two subsystems. A special linear star coupled dynamical network was proposed to limit the influence of some problems (Duan et al., 2007).

During last years it was proven that it seems to be perspective to combine predictive and decentralized control, for example unconstrained networked decentralized model predictive control (Vaccarini et al., 2009) or fuzzy and neural networks, such as adaptive decentralized control using recurrent fuzzy neural networks (Hernandez and Tang, 2009). Another task is to use automatic decentralized control structure selection (Jørgensen and Jørgensen, 2000).

Adaptive control enlarges the area of usage at decentralized controllers. Adaptive control does not limit at linear systems, it can deal for example with time delay (Shah et al., 1997).

Another possibility is to use the predictive control with the combination with adaptive control (Clarke, 1996). Nice paper summarizing the results and applications at adaptive control of nonlinear systems was written by Marino (Marino, 1997).

The chapter is organized in the following way. After introduction, there is a literary research dealing with decentralized control and adaptive control. Next part of the chapter describes chosen method of multi model decentralized control with the results of experiments.

2. Decentralized control

2.1 Nonlinear systems

This subchapter deals with the following: The gap metric approach applied on nonlinear multi-unit plants, linearized model of the nonlinear chemical plant, decentralized power controllers which reduces the disturbance to the power frequency.

A gap metric approach is one of the approaches used for decentralized control (Lee at al., 2000). The plants were multi-unit and they displayed nonlinear behavior. This method has two measures that characterize stability and performance of a controller and are derived from robust control theory. In the paper written by Li at al. (Li et al., 2000), a common design strategy for decentralized control of a chemical process is given. It generates a linearized model of the nonlinear plant and then designs a decentralized robust controller based on the linearized model. Decentralized power controllers are designed in paper (Guo et al., 2000). It is an application of nonlinear decentralized robust control to large-scale power systems with the usage of nonlinear bounds of generator interconnections, which achieves less-conservative control gains. Decentralized controller design for power systems is popular (Xi et al., 2002). The paper is dealing with a multimachine power system as a Hamiltonian control system with dissipation and its decentralized excitation control solving the problem of disturbance attenuation simultaneously.

2.2 Large-scale systems

The mentioned papers of this subchapter solve the problem of continuous decentralized output feedback stabilization, decentralized holographic-structure controllers with unmatched uncertainties, linear constant decentralized controllers for such systems, decentralized state-feedback and variable structure controllers.

The problem of continuous decentralized output feedback robust stabilization is successfully solved by Yan and Dai (Yan and Dai, 1998). It was studied for time-varying nonlinear large scale systems, in which general interconnection and fully nonlinear nominal subsystems were considered. Robust decentralized holographic-structure controllers (DHSCs) are given by Yan et al. (Yan et al., 1999). In this paper, robust control for a class of nonlinear large-scale systems possessing similar subsystems is considered. In the paper written by Ni and Chen (Ni and Chen, 1996), the method for the design of linear constant decentralized robust controllers for a class of uncertain interconnected systems is presented. Ugrinovskii et al. (Ugrinovskii et al., 2000) solved the decentralized state-feedback stabilization. In the considered class of uncertain large-scale systems, the interconnections between subsystems are described by integral quadratic constraints. Variable structure controller was also used in decentralized control (Tsai et al., 2001). The introduction of two sets of switching surfaces in the sliding phase together with the new invariance conditions were given, meaning the sliding mode was used. The usage of decentralized receding horizon control was proven as useful (Keviczky et al., 2006).

2.3 Autonomous control

This subchapter solves the question of autonomous decentralized systems and swarm intelligence, provides application of such systems in Gensym G2 environment on the evaporating system or control of the bio-chemical reactor for separating a gas phase from a liquid phase.

The question of autonomous decentralized systems and swarm intelligence is solved by Koshijima et al. (Koshijima et al., 1996). In the paper, authors present the framework of processing systems design and operations on the basis of the autonomous decentralized system concept. This approach was verified in Chiyoda Corporation in Yokohama, Japan. Application of autonomous decentralized systems was also done in Gensym G2 environment on the multi-effect evaporating system (Koshijima and Toki, 1997). The authors give the realization method on control system, the autonomous decentralized chemical plant (ADChP), the special term and the design of the communication system. Decentralized autonomous control system based on computer technology of fieldbus for reducing the operative personnel in Japanese plant in practice is given by Egi (Egi, 1997).

2.4 Robust control

Robust control is a very popular approach in decentralized control. For instance, the robust exponential decentralized stabilization is solved. Moreover, the usage of RGA is mentioned as well as the J-spectral factorization in decentralized suboptimal control is discussed. The design of robust control for interconnected systems with time-varying uncertainties is also solved. The idea of combination of the decentralized and centralized control is also given. There exists also a combination of adaptive and robust decentralized control, for instance decentralized model reference adaptive control. Robust control of unstable systems is another solved task of decentralized controllers.

The question of decentralized stabilization is formulated and solved by Guan et al. (Guan et al., 2002), namely the robust exponential decentralized stabilization for a class of large-scale, time delay, and uncertain impulsive dynamical systems. Samyudia et al. (Samyudia et al., 1995) proposed a new approach to decentralized control design. In decentralized control design, interaction measures such as the Relative Gain Array (RGA) and the Block Relative Gain Array (BRGA) are commonly used, especially to screen alternative control structures, as the authors says. Another way is based on interaction measures based upon the structured singular value, μ. Decentralized global robust stabilization was also presented by Xie and Xie (Xie and Xie, 2000). The paper focuses on a class of large-scale interconnected minimum-phase nonlinear systems with parameter uncertainty and nonlinear interconnections. J-spectral factorization in decentralized controller and suboptimal controller design for two-channel systems is mentioned by Seo et al. (Seo et al., 1999). In paper by Yang and Zhang (Yang and Zhang, 1996), the decentralized robust control design for a class of interconnected systems with time-varying uncertainties. The idea of combination the decentralized and centralized control is given by Guo et al. (Guo et al., 1999). The problem of decentralized H-infinity almost disturbance decoupling for a class of large-scale nonlinear uncertain systems in the absence of matching conditions was solved. The question of global decentralized robust stabilization is solved by Liu and Huang (Liu and Huang, 2001). The stabilization was done for a class of large-scale interconnected nonlinear systems with uncertainties. Makoudi and Radouane (Makoudi and Radouane, 1999) presented the decentralized model reference adaptive control (DMRAC). The controlled subsystems are interconnected subsystems with unknown and/or time delay. The totally decentralized adaptive stabilizers are formulated by Zhang et al. (Zhang et al., 2000). The paper presents a scheme of for stabilizers for a class of large-scale subsystems having arbitrary relative degrees. The attention to the robust decentralized controller design for unstable systems is paid by Loh and Chiu (Loh and Chiu, 1997). The stable factorization approach is used for facilitating the independent design for open-loop unstable processes.

2.5 PI control

The papers dealing with PI control formulates the guide lines for the tuning and the evaluation. PI controllers might be obtained by minimizing a robust performance criterion using mu-synthesis, for instance, or might be used in HVAC control systems in buildings helping to reduce energy use.

Pomerleau and Pomerleau (Pomerleau and Pomerleau, 2001) gave the guide lines for the tuning and the evaluation of decentralized and decoupling controllers were. In particular, the design of single-input single-output (SISO) controllers for highly coupled multivariable processes often leads to poor performance because of a bad choice of manipulated variables, poor specifications and poor tuning of the controllers. One of the very interesting methods of decentralized robust control is also presented by Gagnon et al. (Gagnon et al., 1998). The PI controller tunings are obtained by minimizing a robust performance criterion and the minimized cost function is derived from the standard mu-synthesis criterion and it takes into account the process uncertainty and desired performance. The usage of decentralized control loops in HVAC control is given by Jetté and al., (Jetté and al., 1998). HVAC control systems in buildings help reduce energy use, this paper is concentrated on PI control of dual duct systems.

2.6 Automatic tuning

Automatic Tuning was described in the theoretical way. It consists of two phases. In the first, the desired critical point consisting of critical gains and a critical frequency is identified when the controllers are replaced by relays. In the second stage, the data of the desired critical point is used to tune the PID controllers by the Ziegler-Nichols rules or their modifications.

Halevi and al. (Halevi at al., 1997) presented the automatic tuning for decentralized control, namely decentralized PID control in multi-input multi-output plants, which had generalized the authors' auto-tuner. Their algorithm consists of two phases. In the first, the desired critical point consisting of critical gains and a critical frequency is identified when the controllers are replaced by relays. In the second stage, the data of the desired critical point is used to tune the PID controllers by the Ziegler-Nichols rules or their modifications. Decentralized controller is taken as a matrix main diagonal controller. The automatic tuning session is successful however the curse is very oscillating. Automating of decentralized controllers is one of the most important parts in decentralized control as it is evident from the paper written by Palmor et al. (Palmor et al., 1995), where the automatic tuning of decentralized PID controllers for TITO processes is given. In paper written by Wang et al. (Wang et al., 1997), a method for automatically tuning fully cross-coupled multivariable PID controllers from decentralized relay feedback is given together with the techniques for process frequency-response matrix estimation and multivariable decoupling design.

2.7 Other strategies

All other approaches are summarized in this subchapter named as Other strategies, for instance the linear quadratic decentralized pole location problem. The other important area is the decentralized control using neural networks or decentralized supervisory control or decentralized internal model control.

Linear quadratic decentralized pole location for singularly perturbed systems is presented (Garcia et al., 2002). The LQ control problem with pole location in a sector is solved using the LMI approach and the decentralized control problem is solved in the reduced slow system using structure constraints on the matrix variables using the state-space formulae. The decentralized control using the neural networks is given by Napolitano et al.

(Napolitano et al., 2000). The paper describes the performance of a neural network-based fault-tolerant system within a flight control system. The nonblocking decentralized supervisory control of discrete event systems is studied by Takai and Ushio (Takai and Ushio, 2002). A modified normality condition defined in terms of a modified natural projection map was introduced there. Decentralized internal model control (IMC) design method is described by Tan and Chiu (Tan and Chiu, 2001). The stability problem of symmetric state-space systems by means of decentralized control is also concerned (Yang et al., 2001). It was shown that the set of decentralized fixed modes of a symmetric system is equal to the set of uncontrollable and unobservable modes of the system. Delay-feedback control using decentralized controller is presented by Konishi and Kokame (Konishi and Kokame, 1999). It is the control of a one-way coupled ring map lattice. The paper considering a decentralized H-infinity control problem for multi-channel linear time-invariant systems with dynamic output feedback was also given (Zhai and al., 2001). The control problem was reduced to a feasibility problem of a bilinear matrix inequality (BMI) solved by using the homotopy method. Another approach to decentralized feedback control is given by El Kashlan and El Geneidy (El Kashlan and El Geneidy, 1996). It is based on eigenspectrum assignment for a large-scale system composed of symmetrically interconnected subsystems preserving the autonomy of the subsystems with sharing the global assignment process using the state space formula. Decentralization in a decentralized static output feedback framework facilitating the use of a quasi-Newton optimization algorithm is described by Corrado et al. (Corrado et al., 1999).There is given a scheme for synthesis using two controllers cascading them in the feedback loop and optimizing over the five free controller parameters, the relative degree two controller. It is important to emphasize that decentralized control as all other control strategies besides its positive features has also some drawbacks meaning that in some cases pure decentralized control becomes inadequate. One of the possible solutions is given (Cho and Lim, 1999) and is based on combination of centralized and decentralized control in supervisory control. Decentralized control dealing with the effects of recycle streams on the controllability of integrated plants and the improvement of performance by a direct compensation of the recycle was used by Scali and Ferrari (Scali and Ferrari, 1999). The global process was decomposed in two parts, one representing the process without recycle and the other one representing the recycle. The decentralized control of plants with uncertain mathematical models is studied, too (Andersson and Marklung, 2000). In particular, it is assumed that the plant is described by a continuous LTI model, which is contained in a specified family P of plant models, and in this case it is assumed that a family of decentralized controllers has been found to satisfactorily control the models contained in P.

2.8 Important areas

A methodology for decentralized control in real-time was proposed (Törgren and Wikander, 1996). An engineering methodology for evaluating different hardware structures, control-system structures and allocation approaches was outlined. It consists of the following steps: control system structuring, decentralization involving partitioning, allocation and evaluation, and execution strategy. The generalization of the concept of contractibility of decentralized control laws in the Inclusion Principle is described by Stanković and Šiljak (Stanković and Šiljak, 2001). A general definition of the contractibility of dynamic output controllers for linear dynamic systems was given together with a discussion related to different restriction and aggregation types adding the contradictory requirements for state controller and observer contractibility. Frequency domain analysis of oscillatory modes in decentralized control systems was given (Calazans de Castro, Silva de Araújo, 1998). In large systems and particularly in the case of systems with interconnected subsystems, different kinds of oscillatory modes (OM), with specific features, can occur. In decentralized control, there exists the static output feedback decentralized stabilization problem, which is solved (Cao et al., 1998). It is addressed using an iterative linear matrix inequality approach together with the derivation of sufficient condition for static output feedback decentralized stabilizability for linear time-invariant large-scale systems. The performance limitations in decentralized control have also been discussed (Cui and Jacobsen, 2002). The authors consider performance limitations from non-minimum phase transmission zeros of other subsystems across the imaginary axis. In paper by Gündes and Kabuli (Gündes and Kabuli, 1996), the reliable stabilization with integral action is studied in a linear, time-invariant, multi-input, multi-output, two-channel decentralized control system, where the plant was stable. The objective was to achieve closed-loop stability when both controllers act together and when each controller acted alone. The choice of the structure of interconnections between manipulated variables and controlled outputs is the task of another paper (Schmidt and Jacobsen, 2003). It is an important task in the design of decentralized control systems for multivariable plants. Instead of the approaches addressing the stability properties of the overall system such as the RGA, the paper focuses on performance, considering the problem of selecting control structures that enable a desired performance proposing the decentralized relative gain (dRG). The stabilization of decentralized control systems might be realized by means of periodic feedback (Lavei and Aghdam, 2008). According to Chen and Seborg (Chen and Seborg, 2003), the closed-loop stability of the decentralized systems using PI controllers can be guaranteed by Nyquist stability conditions. However, a detuning factor for each loop is established and based on a diagonal dominance index. Decomposition is an approach that is connected with decentralized or decoupling control (He and Chen, 2002), namely the structural decomposition of general single-input and single-output linear singular systems. For nonlinear interconnected systems, it is useful to have decentralized observation (Dhbaibi et al., 2009).

2.9 Integral controllability

Decentralized integral controllability (DIC) is one of the very interesting control tasks (Lee and Edgar, 2000). It concerns the existence of stable decentralized controllers with integral action having stable independent detuning. The only information needed for DIC is the steady state process gain matrix. The conditions for decentralized integral controllability were also given (Lee and Edgar, 2002). The first step in designing decentralized controllers is the pairing between manipulated variables and controlled variables. Decentralized integral controllability (DIC) addresses most of the advantages of decentralized controllers over multivariable controllers and is especially useful to eliminate unworkable pairings.

3. Applications

3.1 Industry

The paper by Bakule et al. (Bakule et al., 2002) solves the problem of influence of several different earthquakes onto the two-tower-cable-stayed-bridge. The bridge can be divided into two parts, the subsystems, which influence each other via the middle part of the flooring between the towers. The value of the horizontal forces acting upon the flooring is controlled. In paper by Watanabe (Watanabe, 2002), there is controlled the system turbine – governor in the electricity supply system. The suppression of the low-frequency oscillation in the electricity supply system is the control objective. The contribution written by Cui et al. (Cui, 1999) uses the decentralized theory of control for control of the interconnected electric supply systems with many machines. Each local controller is designed for each generator model. The control was used in the Chubu power plant in Japan. The paper by Aschemann et al. (Aschemann et al., 2002) makes use of the decentralized approach at the control of the Iveco DLK 23-12CS rotating car ladder trajectory employed e.g. by the fire brigades. There is also used the decentralized approach at the milling (Harakawa et al., 1999). The procedure came into existence because of the Nippon Steel corporation, the control system was shipped by the Toshiba company. The works which compare model predictive control with decentralized control we also performed (Lundström and Skogestad, 1995). A comparison of decentralized extended PID and model-based predictive multivariable control was also realized (Pomerleau et al., 2003). The paper is dealing with the cooling zone of an induration furnace where a moving bed of solid pellets had to be cooled for process operation requirements and energy recycling, two fans were used to force the cooling air circulation.

Heat, ventilation, and air-conditioning (HVAC) systems require control of environmental variables such as pressure, temperature or humidity and therefore it is possible to use the decoupling PID auto-tuning of such multivariable systems as presented by Bi et al. (Bi et al., 2000). The algorithm was verified on the cooling-only HVAC pilot plant system and on the air handling units of a commercial building in Singapore. Decentralized control was also used for control of retrofit heat-exchanger networks (HEN) (Uztürk and Akar, 1997). The decentralized optimal control theory allows us to use it for control of chaos in nonlinear networks (Oketani et al., 1995). It is a practical application for stabilizing any specific unstable periodic orbit embedded in a chaotic attractor extended to chaotic nonlinear networks. There was also developed a decentralized control for the Tennessee Eastman Challenge Process, so called TE problem (Rickler, 1996). The design procedure begins with the selection of the method for production-rate control, to which inventory controls and other functions are then coordinated. Nice application of robust decentralized control was also realized for the large scale web handling system, namely for the winding system, experimental set-up with 3 motors and 2 loads cells (Benlatreche et al., 2008) or decentralized robust control of boiler system (Labibi et al., 2009).

3.2 Power systems

Another method for decentralized controller design in power systems was developed by Yang (Yang et al., 1999). The proposed algorithm was applied to the decentralized design of a power-system stabilizer for a model of 10-machine power system. Nonlinear adaptive closed-loop decentralized stabilizing control of multimachine systems is given by Hu et al. (Hu et al., 2002). The system is with unknown parameters and the method is used for the excitation control of power systems. The verification was realized on a 6-machine 22-bus system. A robust decentralized excitation nonlinear control is devoted by Wang et al. (Wang et al., 1997). It was designed for mutimachine power system transient stability enhancement. Nice application of multimachine power system was realized by De Tuglie et al. (De Tuglie et al., 2008), the feedback-linearization and feedback-feedforward decentralized control was used.

3.3 Social sciences and economy

A decentralized control of a two-level distribution system with one central warehouse and *N* non-identical retailers is a control task of the multi-echelon arborescent system (Andersson and Marklund, 2000). Such a system is a member of the supply chain and is decomposed for easily control. The usage of decentralized control in economy and management appears to be adequate at the large. The mathematical model of this multi-level stochastic system with from time to time emerging variable time delay was created. The objective is to optimize the cost in all parts of the system and for that purpose the method of approximate cost evaluation with a modified cost-structure at the warehouse is used. A systematic approach of the analysis of the minimum control requirements that are imposed on power producing units in the Netherlands, in the case when decentralized production increases are studied (Roffel and de Boer, 2003). First, an overview of the amount and type of power production is given. Then the UCTE (Union pour la Coordination de la Transport de l'Electricity) power system model is introduced and tested against frequency and power measurements after failure of a 558 MW production unit. An application of decentralization in production, manufacturing and logistics is given by Jørgensen and Kort (Jørgensen and Kort, 2002). There is studied an optimal control problem of pricing and inventory replenishment in a system with serial inventories, centralized and decentralized decision making is realized. A setup in management of two stocks is decentralized such that pricing decisions are made by the store manager.

3.4 Nature and ecology

Decentralized control is used in branches of the sciences and practical application. The paper written by Bottura and Cáceres (Bottura and Cáceres, 2002) uses the decentralized algorithm for control of the oxygen demand and biochemical oxygen demand with usage of the water works in each parts of the river bed, and thereby the water quality control in the river. The watercourse can be divided into the set of the serially interconnected subsystems.
The decentralization phenomenon can also be observed in the open air, e.g. at the behavior of the one type of the animals group. Tian et al. (Tian et al., 1999) are interested in the fish school. The fish school is a typical example of the autonomous decentralized system and self-organizing system typical for the open air because it shows the high level of coordinated behavior in the leader absence. The authors created the mathematical models of heterogeneous fish school and verified it during the repeated forced modification of the school fish movement direction.

4. Adaptive control

The strategies employing the decentralized adaptive control for motion control of uncertain electrically-driven manipulators have also been presented (Colbaugh and Glass, 1996). One of the approaches ensures semi-global asymptotic convergence of the error to an arbitrary small neighborhood of zero in the presence of bounded disturbances the other one ensures the arbitrarily accurate tracking in the presence of bounded disturbances. These approaches were verified on the six DOF terrestrial manipulators and on the free-flying space manipulators consisting of one or more arms mounted on a space vehicle. The problem solution of completely decentralized adaptive control of large-scale systems is also described (El Adel et al., 1999).Each subsystem is modelled by an orthonormal Laguerre network put in state-space form and decentralized predictive control. Decentralized adaptive control is also used in the problem of controlling the motion of nonholonomic mechanical systems in the presence of incomplete information concerning the system model and state as presented by Colbaugh and Glass (Colbaugh and Glass, 1998). The integrator backstepping approach together with an adaptive law using parameter projection is employed to design robust decentralized adaptive controllers in paper (Wen and Soh, 1997).

There is a quite interesting task to use decentralized adaptive control at systems with nonlinearities at the input, such as dead-zone. This was solved for example by Zhou (Zhou, 2008).

Nice summary paper about the adaptive control was written by Anderson and Dehghani (Anderson and Dehghani, 2008). The paper was written with respect to three types of challenges to adaptive control in the view of the authors. The paper has more than one page of interesting references. Mainly two challenges are interesting and should be mentioned – difficulties that have frequently been overlooked and issues to which researchers look nowadays. The mentioned difficulties or problems of adaptive control according to the authors are: impractical control objectives, transient instability, suddenly unstable closed loops, changing experimental conditions. Another fact is the following - the adaptive algorithm works only under given assumptions. The question is what happens if the assumption is not fulfilled, for instance the controller has frozen parameters and the plant-controller closed loop is unstable or if it is necessary to divide in the algorithm by value close to zero – the signals will be enormous and have to be limited. Another question is the possibility of adaptive control to overcome the unexpected instabilities such as the component failure. However, too fast changes in adaptive controllers are dangerous, the adaptive control needs certain time to overcome the instabilities and sometimes it is not enough. It is always useful to have some a priori information about possible instabilities and failures. Next chapter of the paper discuss the permanent and future of adaptive control. It provides information about multiple model adaptive control, model-free adaptive control and formulates and verifies the method of validating controllers via closed-loop data. Multiple model adaptive control provides nice alternative to pure adaptive control especially in the case of linear plants but it can be used in the case of nonlinear systems control, too. This approach has incorporated the supervisor which is responsible to switch among the controllers in the case the performance is not satisfactory. But there are also problems with the implementation of supervisor, for example the destabilising controller cannot be switched instead of the controller with low performance but stabilizing. Each controller has to be tested before it is switched. Model-free adaptive control does not require the identification of the model, it simultaneously forecasts the performance of all controllers before one is chosen. This strategy leads to the unfalsified adaptive control.

Historically, robust and adaptive control was two approaches competing with each other, but it turned out that it was useful to join the results from both approaches for example for plant model identification in closed loops (Landau, 1999). According to this paper, adaptive control is used for reducing the uncertainty level of the model by using appropriate plant model identifier and robust controller deals with designing the controller in the presence of plant uncertainties. Landau provides the list of necessary needs for a high-performance control system and enlarges it by the detailed description of each one. He mentions important fact from practice that the same data can be used for identification of the model and for the controller validation and that the major improvement in performance occurs after the first identification in a closed loop.

There are many processes in practice that are not linear. Special attention was aimed at systems with time-delay. For such processes, the nice algorithm was proposed (Shah et al., 1997) and it is called as simple adaptive control. The paper provides interested summary of classical adaptive control schemes, such as model reference adaptive control (MRAC), self-tuning regulator (STR) and generalized predictive control (GPC).

5. Decentralized adaptive multi model control

5.1 Theoretical background

This approach is based on the combination of two methods previously published by Perutka (Perutka, 2009, Perutka and Dostalek, 2009). In one paper, there was published the real-time control of rewinding machine by self-tuning decentralized controllers (STC) and initial data for on-line identification were obtain before, using so called pre-identification procedure (Perutka, 2009). Another paper employed simple nonlinear controller (SNC) and added it into adaptive procedure (Perutka and Dostalek, 2009). This method used higher order of plant than classical self-tuning.

Now, we combined these two methods together using the supervisor. The real system is partly identified before the control using the pre-identification. After that, the real-time control is performed. In each time instant, the system is identified by on-line identification twice – for model using STC and SNC, because SNC uses higher order of subsystems models than STC. There is counted 4 time instants of control error after the actual time instant and weighted for both methods, the lower control error says which model and controller is used. This runs for every subsystem simultaneously with one exemption – time around the changes of set-point values, during that time runs only simple nonlinear controller without identification.

5.2 Apparatus description

Laboratory apparatus CE108, coupled drives apparatus manufactured by TecQuipment Ltd., see Fig. 1, simulates several practical tasks of tension and speed of material during continuous processes. In CE108, the flexible belt is mounted on three wheels. The belt forms the isosceles triangle and the wheels are in the corners of the triangle. Two of the wheels are

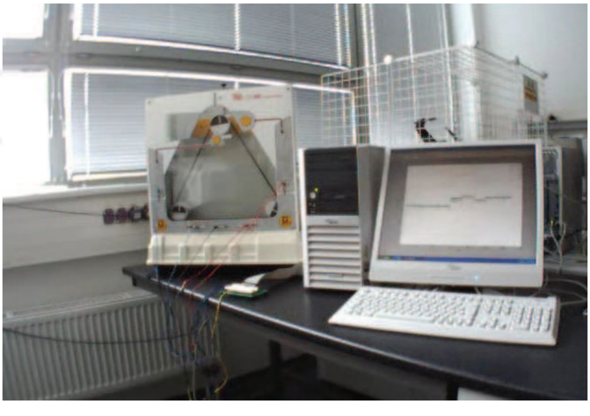

Fig. 1. Photography of CE108 laboratory apparatus connected to PC

connected to the amplifiers of two servomotors and these wheels are fixed. Third wheel, on the top of the apparatus, is mounted on the jib that is connected to the spring. This wheel simulates the workstation. Two servomotors control the speed of all wheels and the belt tension. The speed of the wheels is from the interval 0 – 3000 rpm, which corresponds with the voltage 0 – 10 V. Two control inputs of the apparatus are the control voltages of the servo motors amplifiers, both drives are bidirectional. There are four controlled outputs, the voltage corresponding to the speed of all 3 wheels and the voltage corresponding to tension of the belt. It can be chosen which outputs and how many of them are controlled. The apparatus is connected to the PC via technological card Advantech and via the screw terminal board. The real-time control is realized in MATLAB using Real Time Toolbox. (Perutka and Dostalek, 2009).

5.3 Results of control

The results of control using the method described hereinfore are depicted in figure 2, where sub index 1 is connected with the first subsystem and 2 with second subsystem, u is action signal, y is output signal from the subsystem and w is reference signal.

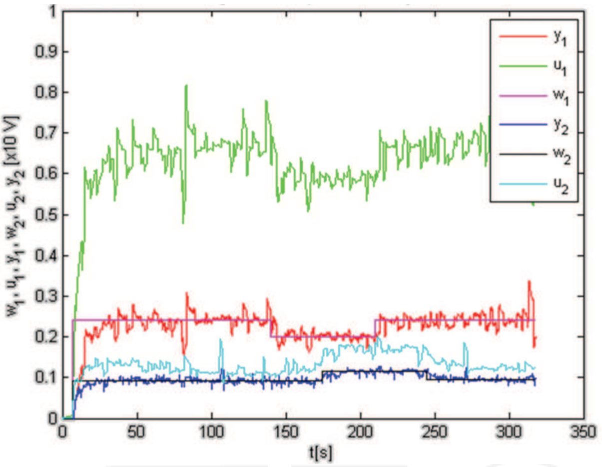

Fig. 2. Results of real-time control of laboratory setup

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7. References

Anderson, B.D.O. & Dehghani, A. (2008). Challenges of adaptive control-past, permanent and future. *Annual Reviews in Control*, Vol. 32, pp. 123-135.

Andersson, J. & Marklund, J. (2000). Decentralized inventory control in a two-level distribution system. *European Journal of Operational Research*, Vol. 39, pp. 483-506.

Aschemann, H.; Sawodny, O.; Bulach, A. & Hofer, E.P.: (2002). Model Based Trajectory Control of a Flexible Turntable Ladder, *Proc. American Control Conference 2002*, Anchorage, Alaska, U.S.A., pp. 921-926.

Bakule, L. (2008). Decentralized control: An overview. *Annual Reviews in Control*, Vol. 32, pp. 87-98.

Bakule, L.; Paulet-Crainiceanu, F. & Rodellar, J. (2002). Decentralized Control Design for a Cable-Stayed Bridge Benchmark, *Proc. American Control Conference 2002*, Anchorage, Alaska, U.S.A., pp. 3046-3051.

Benlatreche, A.; Knittel, D. & Ostertag, E. (2008). Robust decentralized control strategies for large-scale web handling systems. *Control Engineering Practice*, Vol. 16, pp. 736-750.

Bi, G.; Cai, W.J.; Wang, Q.G.; Hang, C.C.; Lee, E.L.; Sun, Y.; Liu, K.D.; Zhang, Y. & Zou, B. (2000). Advanced controller auto-tuning and its application in HVAC systems. *Control Eng. Practice*, Vol. 8, pp. 633-644.

Bottura, C.P. & Cáceres, A.F.T. (2002). Decentralized Control of Serial Interconnected Systems for River Water Quality via Subspace Identification, *Proc. American Control Conference 2002*, Anchorage, Alaska, U.S.A., pp. 3338-3342.

Calazans de Castro, J. & Silva de Araújo, C. (1998). Frequency Domain Analysis of Oscillatory Modes in Decentralized Control Systems. *Automatica*, Vol. 34, pp. 1647-1649.

Cao, Y.Y.; Sun, Y.X. & Mao, W.J. (1998). Output feedback decentralized stabilization: ILMI approach. *Systems & Control Letters*, Vol. 35, pp. 184-194.

Chen, D. & Seborg, D.E. (2003). Design of decentralized PI control systems based on Nyquist stability analysis. *Journal of Process Control*, Vol. 13, pp. 27-39.

Cho, K.H. & Lim, J.T. (1999). Mixed centralized/decentralized supervisory control of discrete event dynamic systems. Automatica, 35, pp. 121-128.

Clarke, D.W. (1996). Adaptive predictive control. *Annual Reviews in Control*, Vol. 20, pp. 83-94.

Colbaugh, R. & Glass, K. (1996). Decentralized Adaptive Control of Electrically-driven Manipulators. *Computers Elect. Engng*, Vol. 22, pp. 383-401.

Colbaugh, R. & Glass, K. (1998). Decentralized Adaptive Control of Nonholonomic Mechanical Systems. *Computers & Electrical Engineering*, Vol. 24, pp. 135-136.

Corrado, J.R.; Haddad, W.M. & Bernstein, D.S. (1999). H2 – optimal synthesis of controllers with relative degree two. *Automatica*, Vol. 35, pp. 1169-1173.

Cui, H. & Jacobsen, E.W. (2002). Performance Limitations in Decentralized Control. *Journal of Process Control*, Vol. 12, pp. 485-494.

Cui, S.; Ukai, H.; Kando, H.; Nakamura, K. & Fujita, H. (1999). Decentralized Control of Large Scale Power System by H-infinity Based Excitation Control System, *IFAC World Congress 1999 Proceedings*, Beijing, P. R. China. CD-ROM, O-7c-06, Elsevier Science.

Date, R.A. & Chow, J.H. (1993). A Parametrization Approach to Optimal H_2 and H_∞ Decentralized Control Problems. *Automatica*, Vol. 29, No. 2., pp. 457-463.

Dhbaibi, S.; Tlili, A.S.; Elloumi, S. & Braiek, N.B. (2009). H_∞ decentralized observation and control of nonlinear interconnected systems. *ISA Transactions*, Vol. 48, pp. 458-467.

Duan, Z.; Wang J. & Huang L. (2007). Special decentralized control problems in discrete-time interconnected systems composed of two subsystems. *Systems & Control Letters*, Vol. 56, pp. 206-214.

Egi, N. (1997). New bio-process control scheme: decentralized autonomous control system. *Journal of Biotechnology*, Vol. 52, pp. 283-288.

El Adel, M.; Makoudi, M. & Radouane, L. (1999). Decentralized adaptive control of linear interconnected systems based on Laguerre series representation. *Automatica*, Vol. 35, pp. 1873-1881.

El Kashlan, A. & El Geneidy, M. (1996). Design of Decentralized Control for Symmetrically Interconnected Systems. *Automatica*, Vol. 32, pp. 475-476.

Gagnon, E.; Pomerleau, A. & Desbiens, A. (1998). Simplified, ideal or inverted decoupling? *ISA Transactions*, Vol. 37, pp. 265-276.

Garcia, G.; Daafouz, J. & Bernussou, J. (2002). The infinite time near optimal decentralized regulator problem for singularly perturbed systems: a convex optimization approach. *Automatica*, Vol. 38, pp. 1397-1406.

Garelli, F.; Mantz, R.J. & De Battista, H. (2006). Limiting interactions in decentralized control of MIMO systems. *Journal of Process Control*, Vol. 16, pp. 473- 483.

Guan, Z.H.; Chen, G.; Yu, X. & Qin, Y. (2002). Robust decentralized stabilization for a class of large-scale time-delay uncertain impulsive dynamical systems. *Automatica*, Vol. 38, pp. 2075-2084.

Gündes, A.N. & Kabuli, M.G. (1996). Reliable Stabilization with Integral Action in Decentralized Control Systems. *Automatica*, Vol. 32, pp. 1021-1025.

Guo, Y.; Hill, D.J. & Wang, Y. (2000). Nonlinear decentralized control of large-scale power systems. *Automatica*, Vol. 36, pp. 1275-1289.

Guo, Y.; Jiang, Z.P. & Hill, D.J. (1999). Decentralized robust disturbance attenuation for a class of large-scale nonlinear systems. *Systems & Control Letters*, Vol. 37, pp. 71-85.

Halevi, Y.; Palmor, Z.J. & Efrati, T. (1997). Automatic tuning of decentralized PID controllers for MIMO processes. *Journal of Process Control*, Vol. 7, pp. 119-128.

Harakawa, T.; Kano, R.; Ogai, H.; Nakamura, R.; Sekiguchi, K. & Kurosawa, R. (1999). Development of Strip Tension Stabilization by Decentralized Control Strategy Based on Advanced Mill Drive System Suppressing Resonant Vibrations in Hot Strip Finisher Mill, *IFAC World Congress 1999 Proceedings*, Beijing, P. R. China. CD-ROM, O-7b-04, Elsevier Science.

He, M. & Chen, B.M. (2002). Structural decomposition of linear singular systems: the single input and single output case. *Systems & Control Letters*, Vol. 47, pp. 327-334.

Hernandez, M. & Tang, Y. (2009). Adaptive output-feedback decentralized control of a class of second order nonlinear systems using recurrent fuzzy neural networks. *Neurocomputing*, Vol. 76, pp. 461-467.

Hu, W.; Mei, S.; Lu, Q.; Shen, T. & Yokoyama, A. (2002). Nonlinear adaptive decentralized stabilizing control of multimachine systems. *Applied Mathematics and Computations*, Vol. 133, pp. 519-532.

Jetté, I.; Zaheer-Uddin, M. & Fazio, M. (1998). PI-control of Dual Duct Systems: Manual Tuning and Control Loop Interaction. *Energy Convers. Mgmt*, Vol. 39, pp. 1471-1482.

Jørgensen, J.B. & Jørgensen, S.B. (2000). Towards automatic decentralized control structure selection. *Computers and Chemical Engineering*, Vol. 24, pp. 841-846.

Jørgensen, S. & Kort, P.M. (2002). Optimal Pricing and Inventory Policies: Centralized and decentralized decision making. *European Journal of Operational Research*, Vol. 138, pp. 578-600.

Keviczky, T.; Borelli, F. & Balas, G.J. (2006). Decentralized receding horizon control for large scale dynamically decoupled systems. *Automatica*, Vol. 42, pp. 2105-2115.

Konishi, K. & Kokame, H. (1999). Decentralized delayed-feedback control of a one-way coupled ring map lattice. *Physica D*, Vol. 127, pp. 1-12.

Koshijima, I. & Toki, A. (1997). Design of Autonomous Decentralized Multi-effect Evaporating Systems. *Computers chem. Engng*, Vol. 21, pp. S107-S112.

Koshijima, I.; Niida, K. & Umeda, T. (1996). A micro module approach to the design and control of autonomous decentralized chemical plant. *Journal of Process Control*, Vol. 6, pp. 169-176.

Labibi, B.; Marquez, H.J. & Chen, T. (2009). Decentralized robust control of a class of nonlinear systems and application to a boiler system. *Journal of Process Control*, Vol. 19, pp. 761-772.

Landau, I.D. (1999). From robust to adaptive control. *Control Engineering Practice*, Vol. 7, pp. 1113-1124.

Lavei, J. & Aghdam, A.G. (2008). Stabilization of decentralized control systems by means of periodic feedback. *Automatica*, Vol. 44, pp. 1120-1126.

Lee, J. & Edgar, T.F. (2000). Computational method for decentralized integral controllability of low dimensional processes. *Computers & Chemical Engineering*, Vol. 24, pp. 847-852.

Lee, J. & Edgar, T.F. (2002). Conditions for Decentralized Integral Controllability. *Journal of Process Control*, Vol. 12, pp. 797-805.

Lee, P.L.; Li, H. & Cameron, I.T. (2000). Decentralized control design for nonlinear multi-unit plants: a gap metric approach. *Chemical Engineering Science*, Vol. 55, pp. 3743-3758.

Li, H.; Lee, P.L., Bahri, P. & Cameron, I.T. (2000). Decentralized control design for nonlinear plants: a ν-metric approach. *Computers & Chemical Engineering*, Vol. 24, pp. 273-278.

Liu, X. & Huang, G. (2001). Global decentralized robust stabilization for interconnected uncertain nonlinear systems with multiple inputs. *Automatica*, Vol. 37, pp. 1435-1442.

Loh, E.J. & Chiu, M.S. (1997). Robust decentralized controller design for unstable systems. *Chemical Engineering Science*, Vol. 52, pp. 2299-2311.

Lundström, P. & Skogestad, S. (1995). Opportunities and difficulties with 5x5 distillation control. *Journal of Process Control*, Vol. 5, pp. 249-261.

Makoudi, M. & Radouane, L. (1999). Robust decentralized adaptive control for non-minimum phase systems with unknown and/or time varying delay. *Automatica*, Vol. 35, pp. 1417-1426.

Marino, R. (1997). Adaptive Control of Nonlinear Systems: Basic Results and Applications. *Annual Reviews in Control*, Vol. 21, pp. 55-66.

Napolitano, M.R.; An, Y. & Seanor, B.A. (2000). A fault tolerant flight control system for sensor and actuator failures using neural networks. *Aircraft Design*, Vol. 3, pp. 103-128.

Ni, M.L. & Chen, Y. (1996). Decentralized Stabilization and Output Tracking of Large-scale Uncertain Systems. *Automatica*, Vol. 32, pp. 1077-1080.

Oketani, N.; Ushio, T. & Hirai, K. (1995). Decentralized control of chaos in nonlinear networks. *Physics Letters A*, Vol. 198, pp. 327-332.

Palmor, Z.J.; Halevi, Y. & Krasney, N. (1995). Automatic Tuning of Decentralized PID controllers for TITO processes. *Automatica*, Vol. 31, pp. 1001-1010.

Perutka, K. (2009). Pre-identification for Real-time Control. *Lecture Notes in Computer Science*, Vol. 5717, pp. 626-632.

Perutka, K. & Dostalek, P. (2009). Simple decentralized autonomous adaptive nonlinear real-time controller with controller source code optimization: Case study, *Proceedings of IEEE International Symposium on Autonomous Decentralized Systems ISADS 2009*, Athens, Greece, pp. 87-92.

Pomerleau, D. & Pomerleau, A. (2001). Guide lines for the tuning and the evaluation of decentralized and decoupling controllers for processes with recirculation. *ISA Transactions*, Vol. 40, pp. 341-351.

Pomerleau, D.; Pomerleau, A., Hodouin, D. & Poulin, É. (2003). A procedure for the design and evaluation of decentralized and model-based predictive multivariable controllers for a pellet cooling process. *Computers & Chemical Engineering*, Vol. 27, pp. 217-233.

Ricker, M.L. (1996). Decentralized Control of the Tennessee Eastman Challenge Process. *Journal of Process Control*, Vol. 6, pp. 205-221.

Roffel, B. & de Boer, W.W. (2003). Analysis of power and frequency control requirements in view of increased decentralized production and market liberalization. *Control Engineering Practice*, Vol. 11, pp.367-375.

Samyudaia, Y.; Lee, P.L.; Cameron, I.T. & Green, M. (1995). A new approach to decentralised control design. *Chemical Engineering Science*, Vol. 50, pp.1695-1706.

Scali, C. & Ferrari, F. (1999). Performance of control systems based on recycle compensators in integrated plants. *Journal of Process Control*, Vol. 9, pp. 425-437.

Schmidt, H. & Jacobsen, E.W. (2003). Selecting control configurations for performance with independent design. *Computers & Chemical Engineering*, Vol. 27, pp. 101-109.

Seo, J.H.; Jo, C.H. & Lee, S.H. (1999). Decentralized H_∞ - controller design. *Automatica*, Vol. 35, pp. 865-876.

Shah, S.; Iwai, Z.; Mizumoto, I. & Deng, M. (1997). Simple adaptive control of processes with time-delay. *Journal of Process Control*, Vol. 7, No. 6, pp. 439-449.

Stanković, S.S. & Šiljak, D.D. (2001). Contractibility of overlapping decentralized control. *Systems & Control Letters*, Vol. 44, pp. 189-200.

Takai, S. & Ushio, T. (2002). A modified normality condition for decentralized supervisory control of discrete event systems. *Automatica*, Vol. 38, pp. 185-189.

Tan, G.T. & Chiu, M.S. (2001). A multiple-model approach to decentralized internal model control design. *Chemical Engineering Science*, Vol. 56, pp. 6651-6660.

Tian, Y.; Sannomiya, N. & Matuda, K. (1999). A simulation study on self-organization in the behavior of a heterogeneous fish school, *IFAC World Congress 1999 Proceedings*, Beijing, P. R. China. CD-ROM, L-5a-04, Elsevier Science.

Törgren, M. & Wikander, J. (1996). A decentralization methodology for real-time control applications. *Control Eng. Practice*, Vol. 4, pp. 219-228.

Tsai, Y.W.; Shyu, K.K. & Chang, K.C. (2001). Decentralized variable structure control for mismatched uncertain large-scale systems: a new approach. *Systems & Control Letters*, Vol. 43, pp. 117-125.

Tuglie, E. D.; Iannone, S.M. & Torelli, F. (2008). Feedback-linerization and feedback-feedforward decentralized control for multimachine power systems. *Electric Power Systems Research*, Vol. 78, pp. 382-391.

Ugrinovskii, V.A.; Petersen, I.R.; Savkin, A.V. & Ugrinovskaya, E.Y. (2000). Decentralized state-feedback stabilization and robust control of uncertain large-scale systems with integrally constrained interconnections. *Systems & Control Letters*, Vol. 40, pp.107-119.

Uztürk, D. & Akar, U. (1997). Centralized and decentralized control of retrofit heat-exchanger network. *Computers chem. Engng*, Vol. 21, pp. S373-S378.

Vaccarini, M.; Longhi, S. & Katebi, M.R. (2009). Unconstrained networked decentralized model predictive control. *Journal of Process Control*, Vol. 19, pp. 328-339.

Wang, Q.G.; Zou, B.; Lee, T.H. & Bi, Q. (1997). Auto-tuning of Multivariable PID Controllers from Decentralized Relay Feedback. *Automatica*, Vol. 33, pp. 319-330.

Wang, Y.; Guo, G. & Hill, D.J. (1997). Robust Decentralized Nonlinear Linear Controller Design for Multimachine Power Systems. *Automatica*, Vol. 33, pp. 1725-1733.

Watanabe, T. (2002). Robust Decentralized Turbine-Governor Control Subject to Saturation Nonlinearity, *Proc. American Control Conference 2002*, Anchorage, Alaska, U.S.A., pp. 1948-1953.

Wen, C. & Soh, Y.C. (1997). Decentralized Adaptive Control Using Integrator Backstepping. *Automatica*, Vol. 33, pp. 1719-1724.

Xi, Z.; Cheng, D., Lu, Q. & Mei, S. (2002). Nonlinear decentralized controller design for multimachine power systems using Hamiltonian function method. *Automatica*, Vol. 38, pp. 527-534.

Xie, S. & Xie, L. (2000). Decentralized global robust stabilization of a class of interconnected minimum-phase nonlinear systems. *Systems & Control Letters*, Vol. 41, pp. 251-263.

Yan, X.G. & Dai, G.Z. (1998). Decentralized Output Feedback Robust Control for Non-linear Large-scale Systems. *Automatica*, Vol. 34, pp. 1469-1472.

Yan, X.G.; Lam, J. & Dai, G.Z. (1999). Decentralized robust control for non-linear large scale systems with similarity. *Computers & Electrical Engineering*, Vol. 25, pp. 169-179.

Yang, G.H. & Zhang, S.Y. (1996). Decentralized Robust Control for Interconnected Systems with Time-varying Uncertainties. *Automatica*, Vol. 32, pp. 1603-1608.

Yang, G.H.; Wang, J.L. & Soh, Y.C. (2001). Decentralized Control of Symmetric Systems. *Systems & Control Letters*, Vol. 42, pp. 145-149.

Yang, T.C.; Zhang, J.H. & Yu, H. (1999). A new decentralised controller design method with application to power-system stabilized design. *Control Engineering Practice*, Vol. 7, pp. 537-545.

Zhai, G.; Ikeda, M. & Fujisaki, Y. (2001). Decentralized H_∞ - controller design: a matrix inequality approach using a homotopy method. *Automatica*, Vol. 37, pp. 1275-1289.

Zhang, Y.; Wen, C. & Soh, Y.C. (2000). Robust decentralized stabilization of interconnected systems with guaranteed transient performance. *Automatica*, Vol. 36, pp. 907-915.

Zhou, J. (2008). Decentralized adaptive control for large-scale time-delay systems with dead-zone input. *Automatica*, Vol. 44, pp. 1790-1799.

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