Hierarchical Control System for Complex Dynamical Plants

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Abstract. The paper is devoted to a concept of hierarchical control for complex dynamical plants and suggests architecture of control system consisting of robust, adaptive, and intelligent levels. Intelligent features of the proposed system are mostly concentrated at the third level incorporated into self-organizing algorithm and decision making approach realized by developers and process engineers. Some results are presented from present groundwork of research performed and future work is outlined. Case study has been chosen from the area of plasma magnetic and kinetic control in tokamak-reactor.

1 Introduction

Recent advances in control strategies, communications, hard and soft-computing technologies have favored an increasing trend towards the new generation of networked control systems for complex plants. The proposal described herein will address the development of scalable control methods and systems in accordance with the Information and Communication Technologies (ICT) Work Programme of the European Commission (EC), the objective ICT-2009 3.5a: Engineering of Networked Monitoring and Control systems with target outcome of Foundations of Complex Systems Engineering [1].

The engineering of networked monitoring and embedded systems is a challenge common to a wide scope of strategic application domains for complex processes. The project is focused on complex automation problems aiming at development of control theory and a framework for future technological and scientific breakthroughs in the conjunction with state-of-the-art of control theory, distributed and embedded computations, communications and intelligent systems. Proposal multidisciplinary fields include *control theory* (multi-sensor systems approach, linear and nonlinear stability, robust and adaptive control, and so forth), *computer science* (reconfigurable architectures, high-performance computations, signal processing, combinatorial optimization, and so forth), networking and monitoring *application-specific issues* (data fusion, fault tolerant and so forth), *network theory* (dynamic QoS management), and *artificial intelligence-based techniques* (fuzzy, neural and neuro-fuzzy systems).

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Interdisciplinary and multidisciplinary essence of this proposal relies on all hierarchical levels of control, from local controllers linked to physical objects (processes) up to networked monitoring and complete managing of complex processes. On the one hand, a key issue is to make control systems easily implemented, self-configuring, and self-optimizing. Proposal goes beyond the current state-of-the-art improving the computational efficiency and the ways in which embedded systems interact with the physical world. On the other hand, the system has to guarantee fault-tolerance and efficiency of networking and monitoring.

To meet the goal stated by the EC a three level hierarchical control system was suggested in Bauman Moscow State Technical University to be applied to solve control problems of complex dynamic plants in science, engineering, and industry.

2 Philosophy of Hierarchical Control

The project is focused on design and development of scalar (Single-Input/Single-Output: SISO) and multivariable (Multi-Input/Multi-Output: MIMO) control systems based on scalable control algorithms for uncertain time-varying nonlinear complex dynamic plants. The major innovation of the proposal implies the elaboration of a new methodology for designing hierarchical adaptive self-organizing control systems to be applied to complex production processes, such as: plasma energy release, chemical and biological processes, casting in metallurgy, oil refinery, and so forth.

2.1 Features of Hierarchical and Heterarchical Control

Today's technologies are enabling complex processes to become more and more autonomous. Industry and academia have investigated a wide range of decentralized control architectures ranging from hierarchical decomposition to a completely decentralized (heterarchical) approach where individual controllers are assigned to subsystems and may work independently or may share data and information.

The main disadvantage of heterarchical approaches is that global optima cannot be guaranteed and predictions of the system's behaviour can only be made at the aggregate level. Hierarchical and heterarchical architectures lie at opposite ends of the distributed control architectures spectrum. The hierarchical approach is rigid and suffers from many of the shortcomings of the centralized approach, whereas it provides clear advantages in terms of overall system coordination alternatively. Despite the large amount of results related with hierarchical control methods, much work has still to be done to extend many theoretical results (stability, performance, robustness) nowadays available from advanced control implementations (H_∞, MPC) and non-traditional control strategies (e.g., neurofuzzy control systems) to the hierarchical structure [2]. In order to synthesize hierarchical control laws, the knowledge of suitable simulation functions is useful. However, an effective characterization of the simulation functions and of the associated interfaces for complex plants is not straightforward [3].

Hierarchical control can be used to integrate extra information (in addition to that concerning the usual control-loop variables such as output, error, etc.) into the control decision-making process. In many situations a hierarchical approach is an advantageous option for process optimization, instead of sophisticated design and implementation of high-performance low-level controllers.

Thanks to its own structural essence, the hierarchical control scheme ensures flexibility and compatibility with other controllers that have already been installed. It has other strong points as well, such as the relatively low cost of investments in improving automation scheme performance, the possibility of exploiting already-installed low-level regulation systems, and the relatively low cost of measurement systems which makes hierarchical control a wise choice from economic and practical viewpoints.

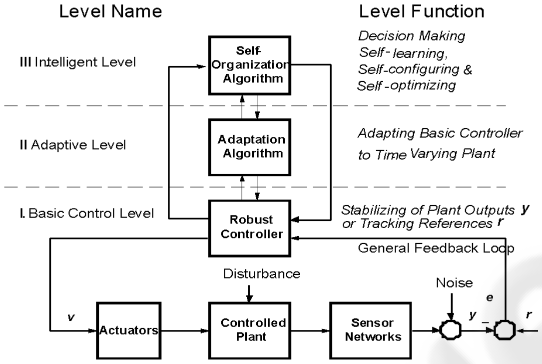


Fig. 1. General configuration of three levels hierarchical control system

2.2 Idea of Three Levels Hierarchical Control System

Whenever hierarchical levels are to be applied, goals and tasks must be broken down into levels of resolution. The architecture of the suggested hierarchical control system is composed of three levels (Fig. 1).

Basic Control Level (I) contains a controlled process under Disturbance, Actuators, Sensor Networks, and a multivariable Robust Controller capable of operation under process uncertainties. Here $\boldsymbol{r}$ is reference action, $\boldsymbol{y}$ is plant output containing Sensor Networks outputs with Noise and measurement inaccuracy, $\boldsymbol{e}$ is an error between reference $\boldsymbol{r}$ and plant output $\boldsymbol{y}$ which is related to the controller input, $\boldsymbol{v}$ is Actuators' input. This level is designed to monitor the process itself and its environment in order to undertake corresponding actions to reject internal and external disturbances and noise in output signals being measured. General Feedback Loop of Basic Control Level is to solve one of two control problems: *Stabilizing of Plant Output* $\boldsymbol{y}$ or *Tracking of Reference* $\boldsymbol{r}$. In the case of unstable process General Feedback Loop is to stabilize plant dynamics. Sensor Networks monitor processing conditions, and if plant input actions are required, changes are made by the Actuators. Robust Controller provides General Feedback Loop capability to work in the presence of plant uncertainties and is to secure acceptable trade-off between robust stability and robust performance.

Adaptive Level (II) contains scalable Adaptation Algorithm which provides *Adapting Basic Controller to Time-Varying Plant* Parameters and Disturbance to achieve the goal of adaptation at this level. Adaptive Level helps Basic Control Level to accomplish closed-loop system trade-off at each discrete moment and to provide the best possible dynamical features of General Feedback Loop.

Intelligent Level (III) with *Self-Organizing, Self-Learning, Self-Configuring*, *Self-Optimizing, and Decision-Making* algorithms has more complex functions. This level is organized by rule base (knowledge base), working memory (facts), and inference engine (rule engine). The rule base contains declarative rules defined by user; the facts are instances of templates to be stored in working memory. The inference engine matches the facts against rules, fires rules, and executes associated actions. The actions are taken by the Robust Controller and carried out by Actuators at Basic Control Level. Adaptation to changing conditions or optimization of control processes is achieved at Self-Organizing Level by changing the structure of Robust Controller, switching separate subsystems on or off, qualitatively changing algorithms of Adaptive Level, changing connections between subsystems and their subordination schemes, and so on.

2.3 Levels Cooperation and Decision Making

The basic difference between Adaptive and Self-Organizing Levels means that Adaptive Level (II) provides tuning of the Basic Control Level (I) mostly through quantitative changes, whereas Self-Organizing Level (III) adjusts lower levels (II) and (I) through qualitative changes. In other words, Self-Organization Algorithm dynamically reconfigures system architectures. At this level self-learning models may be used to get on-line plant parameter and structure changes in order to predict optimal control at each discrete moment.

It is extremely complicated and unreliable to delegate decision making functions at level (III) to artificial intelligent agent. At this level the decision making procedures are assumed to be done by systems developers and process engineers in accordance with the best choice of control algorithms which are the most effective in the case studies and industry applications to complex plants under control (plasma in thermonuclear reactors, oil refinery plants and the like) taking into account expert system database and data knowledge.

3 Statements of Control Problems and Implementation

A number of new important complex control problems have to be studied, discussed and formulated to achieve control goals of acceptable trade-off between robust stability and performance of feedback systems. The problem statements concern the stabilization and tracking process output signals, optimal distribution of process parameters in space in the presence of non-modeled process dynamics, unobserved disturbances, nonlinearities, in particular saturations, wideband insufficiently known noise in output signals, non-minimum-phase dynamics, and time-varying parameters.

To solve these control problems a set of approaches from linear and nonlinear control theory will be explored and developed to achieve scalable H_∞ robust, decoupling, model predictive, adaptive, hierarchy, cascade, soft-computing based control (e.g., neuro-fuzzy control systems), and facilitate decision-making in new appropriate combinations within continuous and discrete time of the three-level hierarchic control system (Fig. 1). Scalable control algorithms mean that the algorithms may be generalized to any numbers of controlled plant inputs, outputs, and space states.

The main scientific and technical contributions of the project imply the integration and synergy achieved as a result of the implementation of advanced control methods, relevant computational strategies and state-of-the-art technologies for embedded and networked systems. In the process of hierarchical structure control systems design the synthesis, analysis, and numerical modeling approaches are proposed to be performed in MATLAB/SIMULINK environment. The controllers to be designed are planned to be implemented in a test bed with primary objective to evaluate functionality of control systems in real time. The test bed should consist at least of two basic electronic blocks: dynamic process model under control and feedback hierarchical controller which interconnection should demonstrate advantages of scalable control algorithms to be elaborated and modern high-performance computations in real time.

4 Case Study of Plasma Energy Release

In order to advance the suggested control approaches plasma energy release case study is planned to be investigated on plasma in tokamaks. Nuclear fusion should be a new source of practically inexhaustible energy and tokamaks are the leaders in thermonuclear energy release area. The plasma control systems under investigation are supposed to be applied to ITER (International Thermonuclear Experimental Reactor).

It is an intense and challenging time for ITER to design the whole set of coupled plasma magnetic and kinetic control systems. Magnetic control systems have to provide accurate control of plasma magnetic configuration [4] and stabilize plasma against the main MHD modes [5]. Kinetic control systems are to control power fusion and power flow to the diverter [6, 7] as well as profiles of plasma kinetic parameters: plasma current, temperature, and density [8].

Reliable control of plasma shape and current in ITER is still a challenging problem because of necessity of controller change during transition from limiter to divertor phases, existence of separate loop to suppress plasma vertical speed of unstable vertical position, currents saturations in poloidal field (PF) coils, and so forth. Plasma tokamak configuration with a free boundary defined by currents in PF active coils and passive contours is described by vector Kirchhoff equation [9] and Grad-Shafranov nonlinear partial differential equation [9, 10]. These equations together with equation of magnetic field diffusion into plasma are realized numerically by DINA plasma-physics code [9].

Plasma magnetic control in ITER is planned to be realized by two-loops control system presented in Fig. 2: fast scalar loop stabilizes plasma vertical speed around zero and slower multivariable loop tracks (on ramp-up and ramp-down phases) and stabilizes (on quasi-stationary phase) plasma shape and current [11].

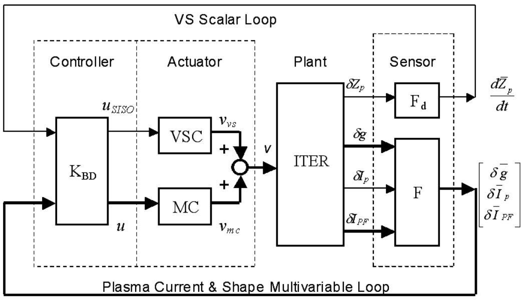
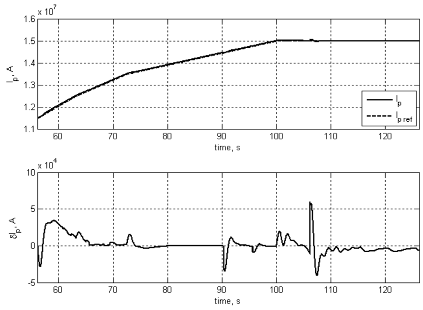


Fig. 2. Two-loops control system: K_{BD} is block-diagonal controller, MC is multivariable main converter, VSC is vertical stabilization converter, F_d is derivative filter, F is filter for plasma shape, current and control currents, g is a vector of gaps between separatrix and the first wall, I_p is plasma current.

Plasma in ITER is a MIMO plant that has 11 inputs (voltages on 11 superconductive magnetic coils) and 19 outputs (6 gaps, plasma current, currents in 11 PF coils, plasma vertical speed). At the moment we have simulation results on DINA code of application of three control methodologies for plasma magnetic control specifically cascade decoupling with PI controllers, H_∞, and Model Predictive Control (MPC). Decoupling approach gave a chance to track plasma current (Fig. 3a) and gaps (Fig. 3b) on the plasma current ramp up phase [11]. In particular H_∞ and MPC control systems were applied at plasma current flat-top phase (Fig. 4a) where MPC showed better performance at minor disruptions but H_∞ system had larger robust stability margin [12].

The fragments of plasma magnetic control were applied for ITER reference scenario 2 with plasma current on flat-top of 15 MA. Multivariable robust controller design (Fig. 1) on level (I) *with adaptation* on level (II) is proposed to be done for the *whole plasma discharge* of plasma current ramp-up, ramp-down, and at quasi stationary stages. It is planned to be applied for ITER reference scenario 2 and for reversed share scenario 4 of plasma current of 9 MA.

The project control methodologies are planned to be advanced to solve *plasma kinetic control problem* as well. Plasma kinetic control means creation and maintenance of *optimal* plasma current, temperature, and density profiles by means of additional heating sources. Such regimes are necessary for stationary operation of tokamak-reactors. As the first step in this direction the kinetic plasma model was created on the base of diffusion equation which dynamically connects 5 inputs from power of heating sources for current drive and 5 outputs that are densities J_p of plasma current at 5 predetermined points of tokamak major radius [13]. For this kinetic model the identification problem was solved at zero frequency and then 5×5 -multivariable controller was designed with the usage of decoupling principle and PI diagonal entries. Controller was simulated on the original kinetic model and showed capability of work in the range of plasma temperature on magnetic axis from 100 eV to 5 keV. Transient process from initial plasma current profile to designated positions at the given points as well as relaxation process after disconnection of the feedback are presented in Fig. 4b [13].


x 10^7
1.6
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I_p, A
60
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time, s
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I_p ref
x 10^4
10
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δI_p, A
60
70
80
90
100
110
120
time, s

One of the main obstacles of plasma control systems design is to solve linearization and identification problems aiming at controller synthesis. In order to improve results on this way one can try to apply modern techniques with the help of neural networks and fuzzy logic. These approaches alone or combined (neurofuzzy) are able to model complex plants without knowledge of plant First Principle Equations using black-box or grey-box modeling approaches. In some cases these models are obtained from experimental input/output data or using simulation data from very complicated original plant models.

5 Intelligent Identification and Control Algorithms

Classic and non-traditional control strategies will be combined in order to incorporate self-* capabilities. Internal-model control (IMC) is a well-established approach to design controllers in which the process model is explicitly used in the control-system design procedure [14]. The use of the IMC paradigm theoretically guarantees control system robustness and stability in the presence of external disturbances. The actual roots of MPC are indeed in the IMC paradigm.

A block diagram of an internal model control based on Artificial Neural Networks (ANN) and Fuzzy Logic (FLC) is depicted in Fig. 5. All disturbances are considered to take place in the process output. In the figure G_M denotes a model of the process (direct model), $G_M{}'$ is an approximate inverse of G_M, G_F is a low-pass filter, L denotes dead-time process plus network-induced delay, G_p denotes the process. The main assumptions are that an approximate reference model G_r is required and a maximum allowable delay (bounded delays) is known to deal with uncertainties and nonlinearities of the controlled process and delays in the corresponding network-based application.

Construction of the IMC system consists of two stages: (**i**) selection of a controller (usually the inverse model) to achieve perfect control and (**ii**) the introduction of a filter.

First an ANN is trained to learn the dynamics of the process and is therefore given known input- and output-data sets. So, one of the neural-network models developed is selected as a basis for IMC control. The inverse model is obtained on the basis of generalized training. Therefore, the network is trained off-line to minimize quadratic criteria $J(\theta)=\sum_{t=1}^{M}\left(v(t)-\hat{v}(t)\right)^2$.

Another ANN is trained to learn the inverse dynamics of the process and to work as a nonlinear controller. The back-propagation of error is applied for tuning $\theta=\left[K_F, K_{CF}\right]$ corresponding to the input scaling factors of the fuzzy block that can replace the inverse model (Fig. 5). The goal is the optimal setting of input scaling factors $\left[K_F, K_{CF}\right]$ to ensure that the overall system follows the reference signal $y'_r(t)$ closely. If inverse model actually describes the inverse dynamic of the plant, there will be a perfect cancellation and we should attempt to find $\theta=\left[K_F, K_{CF}\right]$ such that $v_{\mathrm{NN}}(t) \cong v_{\mathrm{FLC}}(t)$. Using the forward model one can estimate the Jacobians: $\partial y(t)/\left[\partial v(t-1)\right] \cong \partial \hat{y}(t)/\left[\partial v(t-1)\right]$.

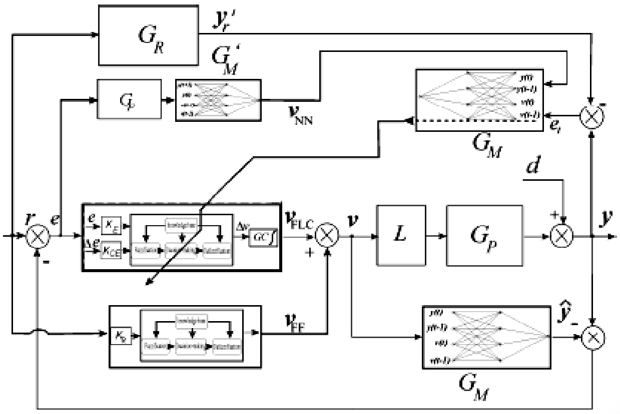

Fig. 5. A tailored scheme based on internal model control with self-learning, feedforward compensation and self-optimization based on ITAE criterion via error back-propagation

An important issue is the stopping condition to avoid overestimating $\theta = \left[K_F, K_{CF}\right]$. The best course is to use the integral of time multiplied by the absolute value of error (ITAE) criterion to optimize the transient response and to penalize lengthy transients $J_2 = \int_0^T t \cdot e(t)\, dt$. The ITAE criterion of J_2 is selected to obtain smaller overshoots and oscillations, which are quite harmful for the cutting tools used in machining.

It is important to remark that hybridization of FLC with ANN can also be applied in the IMC-based approach using other neuro-fuzzy inference systems [15].

6 Conclusions

The concept of three levels hierarchical control system was presented and discussed namely: philosophy of hierarchical control, statement of control problems, implementation, case study of plasma energy release, and intelligent identification and control algorithms.

The project will result in the creation of new process models, procedures of their identification and reduction, efficient, robust, predictable, and safe ICT control methodologies, scalable control algorithms, and high-performance controllers for the problem oriented hierarchical systems under consideration. Scientific, engineering, and industrial results will be accumulated in the data and knowledge bases with accurate classification, qualitative and quantitative assessment, and generalization.

References

1. European Commission C 6827 of 17 November 2008. Work Programme 2009. Cooperation, Theme 3. ICT – Information and Communication Technologies (2008)
2. Scattolini, R.: Architectures for distributed and hierarchical Model Predictive Control - A review. Journal of Process Control, 19 (2009) 723-731
3. Girard, A., Pappas, G.J.: Hierarchical control system design using approximate simulation. Automatica, 45 (2009) 566-571
4. Lister, J.: Magnetic control of a tokamak equilibrium. Proc. of International Workshop: Control for Nuclear Fusion, Eindhoven Univ. of Technology, the Netherlands (2008) www.wtb.tue.nl/cnf/home.php
5. Katsuro-Hopkins, O., Bialek, J., Maurer, D.A., Navratil, G.A.: Enhanced ITER resistive wall mode feedback performance using optimal control techniques. Nuclear Fusion, 47, (2007) 1157–1165
6. Portone A.: The ITER Plasma control challenge. Proc. of International Workshop: Control for Nuclear Fusion, Eindhoven Univ. of Technology, the Netherlands (2008)
7. Leonov, V.M., Mitrishkin, Y.V., Zhogolev, V.E.: Simulation of Burning ITER Plasma in Multi-Variable Kinetic Control System. Proc. of the 32 EPS Plasma Physics Conference, Tarragona, Spain (2005) ID P5.078
8. Labordel, L., Mazon, D., Moreau D., et al.: A model-based technique for integrated real-time profile control in the JET tokamak. Plasma Phys. Control. Fusion, 47 (2005) 155–183
9. Khayrutdinov, R.R., Lukash, V.E.: Studies of Plasma Equilibrium and Transport in a Tokamak Fusion Device with the Inverse-Variable Technique. Journal Comp. Physics, 109 (1993) 193–201
10. Wesson, J.: Tokamaks. 2nd edn. Clarendon Press, Oxford (1997)
11. Mitrishkin, Y., Korostelev, A., Dokuka, V., Khayrutdinov R.: Design and Modelling of ITER Plasma Magnetic Control System in Plasma Current Ramp-Up Phase on DINA Code. Submitted to 48th IEEE Conference on Decision and Control, Shanghai (2009)
12. Mitrishkin, Y.V., Korostelev A.Y.: System with Predictive Model for Plasma Shape and Current Control in Tokamak. Control Sciences, 5 (2008) 22-34 (in Russian)
13. Mitrishkin Y., Dokuka V., Khayrutdinov R., Vertinski A.: Identification and Control of Plasma Current Profile in Tokamak-Reactor. Proc. of VII International Conference System Identification and Control Problems, SICPRO'08, Moscow, Institute of Control Sciences (2008) 1796-1813, ISBN 978-5-91459-002-0
14. Morari, M., Zafiriou, E.: Robust process control. Prentice Hall, Englewood Cliffs, NJ (1989)
15. Gajate, A., Haber, R.E.: Internal Model Control Based on a Neurofuzzy System for Network Applications. A Case Study on the High-Performance Drilling Process, IEEE Transactions on Automation Science and Engineering, 6 (2) (2009) 367-372