From Model-Based Strategies to Intelligent Control Systems

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Abstract: This paper presents the evolution of control systems and trends in the field of integrated computer, communication and cognitive sciences for control applications. There have been selected and presented the most efficient control strategies used in complex process control, as well as the limitations of model-based approaches in cases that imply complex, non-linear and uncertain process models. In this context, the paper presents some trends in robust identification and design of adaptive control systems with a high level of robustness. Concepts for autonomous control of complex systems by the integration of intelligent methodologies are analyzed. Some aspects of hybrid intelligent control are considered and new directions of research towards creating a new generation of control systems are presented. The paper also includes a review of the evolution of computer controlled applications and a new paradigm - C_4 - is analyzed from concept to application. Therefore, the transition from C_2 to C_4 paradigm is illustrated in the context of integrating computers, communication and cognition in control. Finally, advanced control techniques for manufacturing are presented, including intelligent agents, leading to large Intelligent Manufacturing Systems. Some trends in the control of complex systems are presented, including multi-agent technology and hybrid systems formalism.

Key–Words: model-based systems, intelligent control systems

1 Introduction

As a scientific domain, automatic control has developed in a close connection to the industry and the overall evolution of science and technology. The evolution of control engineering is closely related to the evolution of the technology of sensors and actuators and to the theoretical controller design methods and numerical techniques to be applied in real-time computing. At the crossroad of several domains such as Mathematics, Information Technology, and Systems' Theory, automatic control has contributed through its development to enhancing knowledge in practically every scientific and technical domain. By applying the concepts that automatic control operates with, domains of science and technology with a major impact on the evolution of society and the economy have been enriched and ennobled. A beneficiary of the progress in electronic technology, information technology and computers, the field of automatic control evolved spectacularly both from a conceptual and practical point of view, particularly in the last decades of the 20th century. Systems' Theory, communications and nanotechnologies, all characterized by solid formal supports, have contributed decisively to a transition from the C_2 paradigm (Computer-Control) to the C_4 paradigm (Computer, Communication, Cognition for Control), a significant step forward in the development of the new generation of control systems. Embedding cognitive elements and intelligent technologies into advanced control architectures allows an increase in the autonomy of control systems. The modelling and control of complex systems by hybrid systems-specific formalisms and multiagent architectures that encompass both formal techniques as well as heuristic technics, are based on such concepts of advanced automatic control as: complex adaptive systems, autonomous systems, completely fault tolerant systems with dinamic hardware and software reconfiguration.

The increase in complexity of processes, together with high performance and safety demands in functioning integrated into a coherent view of sustainable development imposes new criteria for an integrated process and control design. The evolution of nanosciences and nanotechnologies which allow for increasing the knowledge of the human biological system will have a significant impact on the evolution of automatic control systems as well as information and knowledge processing systems.

Automatic control actively contributes to the development of fundamental domains of science (Mathematics, Physics, Biology, Biophysics, Biochemistry, Bioengineering, etc.) in the same time capitalizing on the progress achieved in these domains.

This paper attempts a structuring of the problem of process control from the perspective of the evolution of automatic control and process automation. Section 2 reviews the evolution of control systems and section 3 presents the main strategies of control based on mathematical models. In section 4 some concepts that define the transition to the C_4 paradigm are presented and in section 5 a new vision on a new generation of control systems is introduced. A case study illustrates the current trends in intelligent manufacturing systems.

2 The Evolution of Control Systems Architectures

The control systems architectures are designed based on the complexity of the process to be controlled, the level of the performance requirements imposed, the accessibility of control variables, and, last but not least, the availability of the hardware and software technologies required for an efficient implementation.

The two control principles - feedback and feedforward control - lay at the basis of the main control systems architectures with a wide industrial applicability. A first category of ACS (Automatic Control Structure) which employ conventional control strategies rely to one degree of freedom and two degrees of freedom control based on PID control, ratio control, cascade control, and combined control.

A second category of ACSs, based on advanced control techniques in architectures with one or two degrees of freedom, includes: gain scheduling, decoupling control, selective/override controllers, time delay compensation. Adaptive and optimized control within architectures structured on one or more hierarchical levels, represents a third generation of control systems. This category of advanced control systems encompasses: Adaptive Control, Optimal Control, Model-predictive Control, Internal Model Control, Robust Control, Nonlinear Control, Statistical Quality Control.

A new generation of control systems is rapidly emerging towards industrial applications based on intelligent methodologies such as: Fuzzy Control, Knowledge Based Control, GA, Neural Control, Nonlinear Multi-model Control, within system architectures with one or more degrees of freedom, structured on one or more hierarchical levels.

This fourth generation of control systems encompasses both model-based control strategies, as well as heuristic strategies, prefiguring high autonomy advanced control architectures, organized on multiple levels and hierarchical layers.

For a process characterized by a mathematical model with more or less adequacy to reality, several control strategies can be designed and synthesized on the basis of a linearized model, or of a nonlinear model.

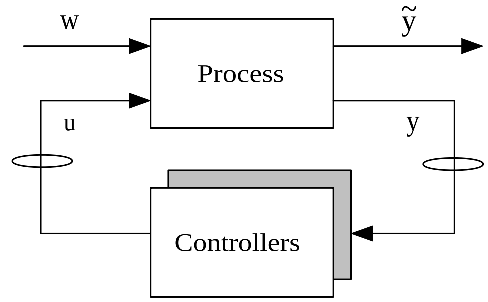

Figure 1:

Figure 1 presents the standard control/command structure with one level organization. Given the model of the process in equations (1),

$$\begin{aligned} \dot{x}(t) &= f_p\left(x(t), u(t), w(t), t\right) \\ y(t) &= g_p\left(x(t), u(t), w(t), t\right) \qquad x_0 \in \mathcal{R}^n \quad (1) \\ \tilde{y}(t) &= h_p\left(x(t), u(t), w(t), t\right) \end{aligned}$$

where $x(t) \in \mathcal{R}^n$, $y(t) \in \mathcal{R}^p$, $u(t) \in \mathcal{R}^m$, $w(t) \in \mathcal{R}^q$, $\tilde{y}(t) \in \mathcal{R}^\alpha$, a nonlinear control strategy can be adopted:

$$\begin{cases} \dot{x}(t) = f_c(x_c, y(t), t) \\ u(t) = g_c(x_c, y(t), t) \end{cases} \qquad x_c \in \mathcal{R}_c^n \qquad (2)$$

or a linear control strategy, such as:

$$\begin{cases} \dot{x} = A_c x_c + B_c y(t) \\ u(t) = F_c x_c + G_c y(t) \end{cases} \qquad x_c \in \mathcal{R}_c^n$$

For a linearized model of the process a linear control strategy can be synthesized, but with the inherent limitations caused by the structured and unstructured uncertainties associated to the simplified model of the process.

Applying some specific methods based on the LQR theory, LQG theory, $H_2|H_\infty$, μ-synthesis techniques, Linear Matrix Inequalities (LMI) design tools, Generalized Predictive Control techniques (GPC, MPC), Adaptive Control Theory, etc., leads to control strategies based on the simplified mathematical model of the process to be controlled. Most often, the use of linearized models of processes results in linear control strategies with a limited robustness of the performances imposed on the control system.

A solution to reduce the fragility of controllers designed on the basis of process models affected by uncertainties is to adopt an adaptive multimodel control strategy (see figure 2).

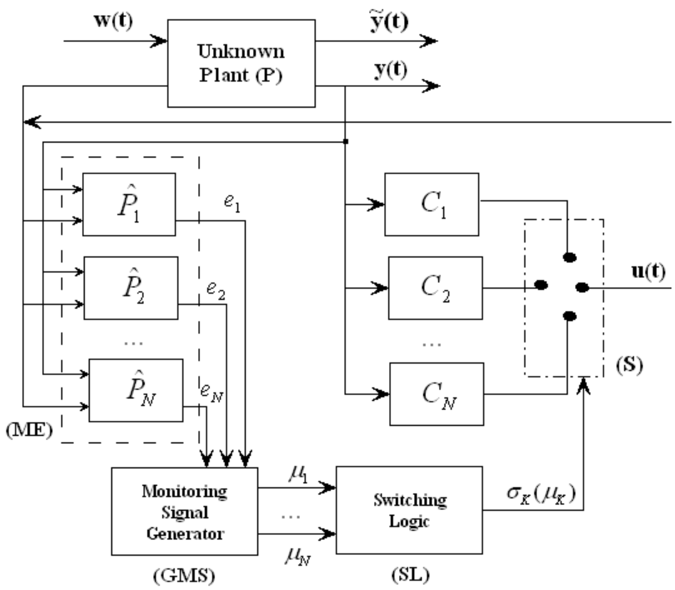

Figure 2:

The structure in figure 2 illustrates the deterministic case of indirect adaptive multimodel control, with distinct functions for the identification of the models, $\hat{P}_k(s)$, and the selection of the controllers, $C_k(s)$.

The prediction errors, $e_k(t)$, computed by the multi-estimator (ME) system block are processed by the monitoring signals generator (MSG) which generates the monitoring signals μ_k. These monitoring signals, defined as a function of the norms of the error estimates, $e_k(t)$, indicate which of the $\hat{P}(k)$ estimated models are ”closer” to the real process.

The C_k controllers are designed such that each of them insures stable desired performances for a certain set of parameters. The selection of the controller is achieved through the operation of the switch S by the signal $\sigma_k(\mu(k))$ which is generated by the switching logic (SL). This switch keeps the command signal σ_k constant for an appropriate time interval in order to avoid a too rapid switching, thus preventing shocks on the process.

The main advances in control theory have been concerned with a deeper understanding of robustness issues and the development of new tools and models to cope with uncertainty. A new theory must be developed in order to be able to handle highly nonlinear complex systems involving an extremely large number of control loops, or the coordination of a large number of autonomous agents, to control nonlinear, hybrid and stochastic systems, and to handle very large model uncertainties.

3 Impact of Information and Communication technology on advanced Control Systems

The advanced communications and networks have a significant impact on future control systems and advanced methodologies associated with control will likewise contribute to further advancements within the communication and networking fields. The future will see many synergistic benefits coming from the joint development of these two fields.

Some results and trends are expected in this very promising context, where control technologies are supported by advanced information and communication technologies:

- Discrete Event Systems and Hybrid Systems are now referred to as a convergence of communications, computing, and control.
- New problems involving complex stochastic systems are expected to appear and must be solved. Randomization methods for robust decision making look very promising and are expected to attract a good deal of attention in the near future.
- The robust design in the future will be based on stochastic techniques, including stochastic robust techniques and randomization approaches.
- New developments in the technology of sensors and actuators will continue to fertilize new control applications fields: medicine, biology, crystallography, optical communications, and nanotechnology. These fields need new efforts for modeling, analysis and design.
- New effective real-time optimal algorithms are likely to be developed for 2D and 3D pattern recognition in cases when more complex sensing and signal processing is used (e.g. for the control of moving objects).
- Design of very large distributed control systems has presented a new challenge to control theory. New theories will be developed to handle highly complex systems, coordination of large numbers of autonomous agents, to control hybrid and stochastic systems and to handle very large model uncertainties.

- ○ Robust control of large-scale systems raises important questions to which some important answers are expected; control over networks will be an important application into embedded real-time control systems area.
- ○ Distributed hybrid control systems involving an extremely large number of interacting control loops, coordinating a large number of autonomous agents, handling very large model uncertainties, need a new vision on control theory and application.
- ○ New dimensions for control will be open from bioinformatics and the application of micro and nanorobots in biology and medicine.

Specific technologies and complex systems will set new quality requirements and new challenges for control systems. Intelligent control of complex distributed systems with moving and cooperating objects could be realized within an Intelligent Space.

4 From the C_2 paradigm to the C_4 paradigm

The implementation of advanced control strategies (GPC, LQG, Adaptive Control, Robust Control, Optimal and Nonlinear Control) on computer networks allowed the development of distributed, real-time control architectures with a significant impact on the automation of complex processes or enterprises. Thus, the C_2 paradigm (Computer for Control) implies all aspects of computer-based control - including real-time computing systems, distributed real-time communication and control systems, hardware and software architectures, development methodologies, software tools and software engineering - that ensure the safe functioning of computer controlled processes.

Developing cognitive systems, or the so-called intelligent systems, implies all the aspects connected to the application of fuzzy, neural, evolutionary, and cognitive techniques (KBS) for process control, including modeling, identification, stability analysis, design, learning, adapting, evaluating and optimizing the functioning of the process.

Incoporating communication aspects and developing telecommunication-based control systems, which allow for providing services to remote equipment, particularily methods of remote and distributed control, remote sensor data acquisition, the Internet, telepresence, teleoperation, telemaintenance, telediagnosis, and teleeducation facilitates the emergence and development of a new class of control systems which embeds all the aspects of intelligent communication.

Much attention was paid during the last decade to the real-time implementation of intelligent control systems including new aspects of control engineering such as: fault detection, fault diagnosis and control system reconfiguration. Telecommunications and cognitive systems define today new paradigms in computer-controlled systems.

A key issue in control engineering is the application to highly complex systems: the coupling of complicated and large heterogeneous systems where several different disciplines are involved and several different types of information are available or have to be uncovered and processed.

We have to define a new paradigm in control engineering called ”Information processing for action” in which Control, Computers, Communication, and Cognition play equal complementary roles in addressing real-life problems, from small-scale devices, to large-scale industrial processes and non-technical applications.

Thus, the C_2 paradigm of ”Computer for Control” is shifting towards the C_4 paradigm of ”Computers, Communication, and Cognition for Control”, providing an integrated perspective on the role that computers and control play for each other. New advances in computers and knowledge management and the rapidly emerging field of telecommunications creates a new vision about advanced control systems.

5 Some Challenges for Control technologies

In the C_4 framework we have to develop a new generation of controllers as ”software-intensive controllers” which have some important features: time-critical, embedded, fault tolerant, distributed, intelligent, large, integrated, open, and heterogeneous. The evolution towards dynamic information systems makes flexibility and hot replaceability key design issues for present and future systems. Local component intelligence is increasing and large distributed controllers are being developed as communities of interacting intelligent agents.

The design support tools need to be developed to automatically generate alternative solutions (models of processes and controllers). Some solutions could be deployed simultaneously into self-organizing controllers, by using evolutionary programming as optimization techniques in an integrated optimal design of process and control strategies.

Biological organisms are equipped with highly efficient, redundant systems for sensing the environment, processing and storing the information acquired. For advanced control-systems, as man-made systems, we can achieve major progress by using much more affordable sensor technologies and by developing new tools to interpret the data acquired and to represent them in the form of knowledge, thus adding truly cognitive functions. The adaptation of control laws, or the complete dynamic reconfiguration of control strategies must be included into the new generation of control systems. The general design philosophy must shift from resource limitation to resource adequacy rendering more understandable solutions possible.

Software-intensive distributed embedded controllers are structured as dynamic collections of autonomous real-time agents interacting with eachother. They have the required levels of autonomy to be effective in their tasks, while keeping interaction to achieve global objectives and modularization to make them easy to use.

Control-based approaches to model, analyze and design embedded computer and communication systems have a real impact on the development of complex real-time systems. Some aspects of control theory application to control timing behavior and optimal, robust or adaptive feedback control in real-time systems are included.

The real integration of control theory in all aspects of analysis and design of real-time embedded computer and communication systems provides new and more efficient tools in advanced control systems.

The new generation of control systems should be able to autonomously control complex, poorly understood processes, such that some well-designed goal can be achieved. The intelligent control systems should cope with changes not anticipated in the process or its environment, learn from past experience, actively acquire and organize knowledge about the surrounding world and plan its future behavior.

The incorporation of intelligent techniques, such as fuzzy logic, neural networks, genetic algorithms, into advanced control systems, by employing alternative representation schemes and formal methods to add additional relevant information that cannot be used in the standard control-theoretical framework of differential and difference equations, represents a new challenge for the control systems community.

Fuzzy logic systems are suitable to represent qualitative knowledge, either provided by human experts, or automatically acquired from data (rule induction, learning). Neural networks can perform complex learning and adaptation tasks by imitating the function of biological neural systems, and thus can be used as models for nonlinear, multi-variable systems, trained by using input-output data observed on the system. Genetic algorithms are randomized optimization techniques successfully applied in searching high-dimensional spaces, for instance in the optimization of model or controller structures and the tuning of parameters in nonlinear systems.

Recent developments in computer networks and communications, combined with new ways of information and knowledge processing, provide new possibilities for control purposes, especially in the area of telematics applications.

The quality of communication networks represents a most important element of assure the stability and performances of remote control systems, for which new concepts of distributed control, real-time communication networks, and autonomous control strategies must be developed. The orientation towards a network-centered view has as a result different architectures of computer control systems, enabling various forms of telepresence.

An important area of application of control theory and engineering is the control of communication networks including variable time delays. A real issue for control engineering is the design and application of instruments and control schemes for telemonitoring, telepresence, and telecontrol.

Main areas of interest for the control systems community in the future will be: agent technology, architecture-based design, artificial intelligence, concurrent engineering, composability, design patterns, distributed embedded systems, model-based software engineering, modular systems, object-oriented programming, product line engineering, real-time distributed systems, re-usabilty, software components and software processes.

A new generation of control systems has to be developed by increasing the autonomy of control systems and their degree of intelligence. By the integration of model-based and intelligent methodologies it is possible to solve the robustness problems in the framework of complexity and large uncertainties. Hybridization of intelligent methodologies by transformation, combination, fusion, and association will increase the autonomy of control systems, while the combination of these hybrid technologies with agent technology could offer valuable solutions for the modelling and control of complex systems.

Some hybrid technologies have to be used to integrate the mathematical models of discrete event and continuous systems with the intelligent techniques and intelligent agents to model and control the complexity.

The most important attributes of the intelligent systems, such as perception, communication, learning, planning, and behavior generation, reasoning and thinking, are more and more included in different forms in the advanced autonomous control systems. The integration of intelligent agents into hierarchical and heterarchical architectures with different time scale and resolution allows for the development of a new generation of control systems organized on the Increasing Precision and Decreasing Intelligence, ”IPDI” principle, as a multiresolutional system.

6 Intelligent Manufacturing Systems - A Case Study

The manufacturing systems in one enterprise or in a network of enterprises is a complex system integrating materials, resources, technologies, information and communication technologies, and most important, knowledge.

An intelligent architecture for manufacturing systems could be organized on different levels of abstraction. The first level of abstraction provides a conceptual framework for viewing the entire manufacturing enterprise as an intelligent system consisting of machines, processes, tools, facilities, computers, software, and human beings, operating over time, and on materials to produce a large number of different products.

The second level of abstraction of intelligent manufacturing systems provides a model to support the development of performance measures and the design of manufacturing systems and software (CAD, CAM, CAE, etc.).

The engineering guidelines to implement specific instances of manufacturing systems such as machining and inspection systems are included into a lower level of abstraction, as depicted in figure 3.

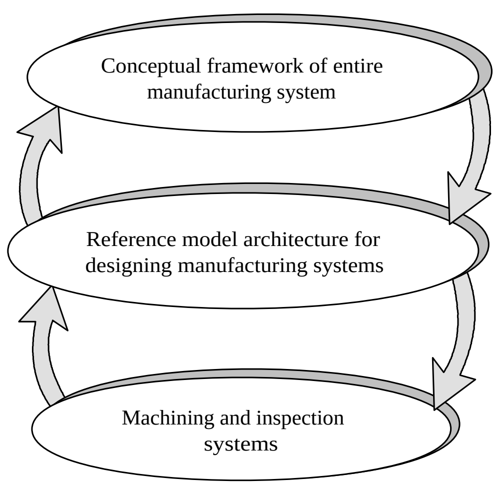

Figure 3:

As a model of intelligent control architecture for manufacturing systems adopts a hierarchical layering with different range and resolution in time and space at each level. For each level within the hierarchy, the functional entities are defined, each with particular responsibilities and priorities, at a compatible level of spatial and temporal resolution. These functional entities receive goals and priorities from above and observe situations in the environment below. In each functional entity (FE) at each level, there are decision making modules to formulate plans and actions in a real interconnection with upper and lower levels. Each FE must have access to a model of the world that enables intelligent decision making, planning, analysis, and reporting activities to be carried out, despite uncertainties and unexpected events in the real world.

The manufacturing enterprise is organized into management units (MU) such that each MU consists of a group of intelligent agents (humans or machines) with a particular combination of knowledge, skills, and abilities. The intelligent agents schedule their activities to achieve the goals of the jobs assigned to them and are expected to make local executive decisions to keep things on schedule by solving problems and compensating for minor unexpected events.

Each unit of management has a model of the world environment in which it must operate and has access to resources of information that keep its world model current and accurate. The world model of each MU includes a representation of the state of the environment and all entities that exist in the environment including their attributes and relations, and the events that take place in the environment.

Therefore the intelligent manufacturing systems consists of many functional elements and management units organized in a hierarchical architecture with well defined attributes and functions realized on different levels of resolution. The functional elements are the fundamental computational units of an intelligent system and include the following main functional modules: sensory perception, world modeling, behavior generation and value judgement. World modeling maintains and uses a distributed dynamic store of knowledge that collectively forms a world model and includes both a model of the manufacturing environment and a model of all the system. These modules are interconnected by a communication system that transfers information and knowledge between them. In this conception we have to integrate a large number of the heterogeneous modules with different levels of intelligence that operate with different levels of resolution on each level of the hierarchy. This intelligent manufacturing system includes computers, communication, cognition, and control functions organized into a hierarchical and heterarchical architecture. For each level the granularity of knowledge imposes the operators: Grouping, Focusing of Attention, and Combinatorial Search to get an optimal decision.

The next generation of manufacturing systems will be characterized by the capacity to adapt to the demands of agile manufacturing with rapid response to changing customer requirements, concurrent design and engineering, lower cost of small volume production, just-in-time delivery, real-time planning and scheduling, increased demands for precision and quality.

By including intelligent control concepts in manufacturing systems the full range of agile manufacturing requirements will be satisfied and the C_4 paradigm has a real application.

Thanks to recent advances in information and communication technologies and intelligent control technologies, the manufacturing world is evolving from highly data-driven environments to a more cooperative information/knowledge-driven environment, placing more emphasis on the the enterprise know-how, common-sense, and application semantics. The management of knowledges and integration of intelligent agents for cooperation allow the solving of the main problems of the next generation manufacturing:

- adaptable, integrated equipment, processes and systems that can be readily reconfigured;
- sustainable manufacturing processes that minimize waste in production and energy consumption;
- innovative processes to design and manufacture new materials and components;
- technologies that can convert information into knowledge for effective decision making;
- product and process design methods that address a broad range of product requirements.

All of these areas are strongly related to the concepts of Enterprise Modeling and Integration and to concepts of Intelligent Manufacturing.

7 Conclusions

The evolution of control technologies is strongly influenced by the evolution in the fields of information theory and technology, communication, computers and cognitive systems. The significant results in the domain of control theory, nonlinear process control, stochastic, adaptive robust control, are conceptually and technologically sustained by significant results in the domains of heuristic control, artificial intelligence, cognitive sciences, nanosciences, and nanotechnologies.

This paper made an attempt to synthesize the main results in the field of advanced control and delineate research direction for the design and implementation of autonomous control systems. Some specific elements are presented for the integration of advanced concepts and technologies in the field of communication and computers with elements specific to intelligent control of high complexity processes. The theory and technology of distributed intelligent agents in applications which require the real-time control of processes is presented as a support of hierarchical and heterarchical architectures which are temporally and spatially distributed and implement the IPDI principle.

The new C_4 paradigm represents the conceptual and applicative framework for autonomous control systems, while the integration of control theory concepts in the design of integrated real-time systems is a real challenge for the expert communities in the field of automatic control, computer science and communication.

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