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Trends in Theory of Control System Design

Status report prepared by the IFAC Coordinating Committee on Design Methods

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Abstract: Control theory deals with disciplines and methods leading to an automatic decision process in order to improve the performance of a control system. 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. New control disciplines, new development in the technologies will fertilize quite new control application fields. Based on the contributions of the Technical Committees within CC2 the status report gives an overview of the current key problems in control theory and design, evaluates the recent major accomplishments and forecasts some new areas. It points out some control fields, which could be challenges for future research.

1. INTRODUCTION

Theory on control design methods traditionally focuses on domains reflected in the TC structure of the IFAC Coordinating Committee on Design Methods (control design, linear control systems, nonlinear control systems, optimal control, robust control). This report summarizes the contributions of all the Technical Committees within the Coordinating Committee. The report has its roots in the milestone report presented at the 16th IFAC Congress in Prague. Necessarily there are some overlaps with the previous report. It attempts to give an overview of the current key problems in control theory and design, evaluates the recent major accomplishments and forecasts some new areas. It points out some control fields, which could be challenges for future research. The summary is based on the contributions of the TC members, who are experts on different areas of control theory, and takes into consideration the results of former IFAC projects on emerging areas and also other summarizing works as well (S.L. Jämsä-Jounela, 2006, A. Isidori et al., 2002, R. Bars et al., 2006, E.F. Camacho et al., 2005, S. Bittanti and M. Gevers ed., 2007).

Control deals with methods leading to an automatic decision process in order to improve the performance of a system (industrial, biological, economical, social, ...). The most significant and most powerful concept in control is "feedback", which means that information about the system, typically either the past evolution of the full state or some measured outputs has to be collected (sensors) and means to act on the system and change its behaviour (actuators) to achieve the desired performance. In between, the central task is to design and implement the control algorithms. In the design process different control algorithms can be considered evaluating how a specific controller could achieve a certain design goal, and then a suitable controller has to be chosen and implemented with appropriate tuning parameters.

Therefore, 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 as well as to numerical techniques both for off-line optimization and on-line real time computing.

We can consider the status of controller design methodology from three perspectives:

- theory
- numerical techniques
- technology/applications

Complex controlled engineering systems should provide guaranteed reliability and performance in the presence of disturbances and noises, variable operating conditions, nonlinearities, system uncertainty and variability, changing environment, actuator limitations, implementation constraints, etc.

Control engineers are faced with the critical problem of reducing costs while maintaining or improving product quality and insuring safe performance. As systems become more complex, an equally important aspect is to insure reliability of the implemented systems. The reliability of hardware and software are, therefore, issues which have to be addressed. In addition, suitably designed man-machine interfaces must enable efficient and reliable information transfer and control management.

Control systems nowadays are becoming more and more complex, involving extremely large number of control loops, distributed networked control systems, coordinating a large number of autonomous agents. Control, computation, communication appear together to solve large scale control problems. Figs. 1, 2 and 3 demonstrate complex processes: an oil-refinery distillation column, an automated production line, and a rolling mill. Operation of such processes requires reliable, well interacting control systems.

New developments in the technology of sensors and actuators along with improved control methods will open the door to new application fields in medicine, biology, crystallography, optical communications, nanotechnology, etc.

New technologies, new application fields require new theories for modelling, analysis and design.

These needs provide several challenging problems for modelling and control.

Fig.1. Distillation column in oil-refinery plant

2. CURRENT KEY PROBLEMS, MAJOR ACHIEVEMENTS, CHALLENGES

2.1 Modelling, identification and control

The topics underlying this issue are in the focus of the IFAC Coordinating Committee on Systems and Signals (Katayama *et al*., 2006). Here we survey on specific topics more closely related to control issues. In fact, in modelling and control there is a need for improved performance, better models, better methods of handling uncertainty, complexity, stability, boundedness, nonlinearity, overcoming random disturbances. Applying such techniques to real applications such as networked systems is a challenge. There is a gap between theoretical methods and their applications. In a number of cases we do not have much knowledge how to start from application requirements and turn them into mathematical formulation that can be solved using analysis and synthesis methods.

Fig.2. Automated production line

This issue gains further importance when we do not have solid knowledge of laws governing system behaviour. This leads to issues of grey box identification. It is important also to investigate the impact of approximations and/or assumptions on the sensitivity of the final design.

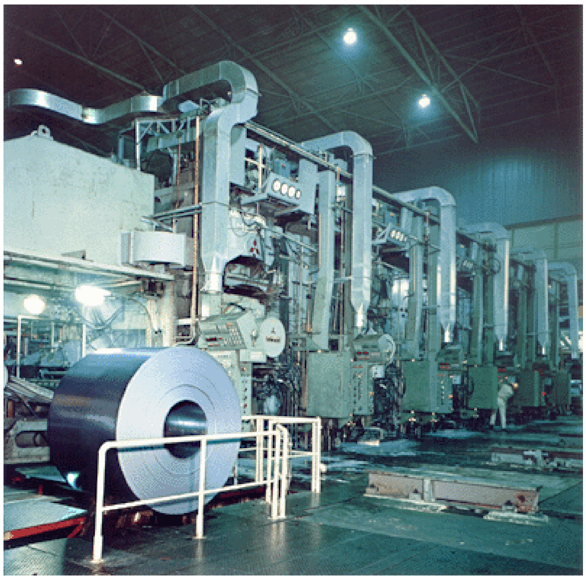

Fig. 3. Rolling mill

New modelling methods are required which should provide a framework where a priori knowledge of the process can be combined with various existing modelling techniques. Controller design methods should be prepared to use such models. Data based identification techniques, data mining algorithms have to be worked out to convert data into knowledge. Several techniques from machine learning proved successful in identification of linear and nonlinear systems.

The practical application of robust control design methodologies depends on the ability to develop appropriate models of physical systems. Model validation provides means of assessing the applicability of a given robust control method (nominal model with linear fractional norm bounded perturbations and norm bounded unknown inputs) with respect to an input-output experiment.

Interplay between identification and control has been investigated, and has to be considered in adaptive control applications.

Besides identification methods based on minimisation of a cost function subspace methods are also effectively used. Identification based on subspace methods provides numerically extremely robust models in state-space form. With subspace methods also structure identification can be handled effectively. These methods can be used also for identification from data collected under feedback.

New theory is needed in order to model and control highly complex systems such as those involving 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. It is a challenge to develop powerful new identification tools that are needed to model large scale systems.

New efforts are needed for modelling systems pertaining new application fields (medicine, biology, crystallography, etc.).

2.2 Complexity and control structure

Increasingly, there is a desire to develop control systems for large-scale complex interconnected distributed systems. There is a need for a good choice of control structures and control techniques for the given problem. We do not have good understanding of the relationship between control structure, robustness and performance. It is clear, that there are trade-offs between these. We have far better understanding of trade-off between robustness and performance, but not so far regarding system structure. The problem becomes even more compelling when one is faced with sensor selection, communication links, computing resources, etc.

It is a question how to combine techniques from robust control analysis and design with other techniques such as adaptive control, nonlinear control, optimal control, etc. Optimization theory and robust control have especially a strong interplay.

Monitoring and control of industrial processes have been of major interest. Intelligent techniques like machine vision and fuzzy logic can also be applied.

Among control structures internal model control is better understood and has gained a lot of effective applications both for linear and nonlinear systems.

2.3 Control algorithms

In process control PI(D) control algorithms are still the most accepted. For practical reasons they are equipped with anti-reset windup properties to handle saturation effect. Robust controller design methods would provide acceptable performance in case of uncertainties (IFAC WS on Digital Control, 2000).

Control design considering structural constraints, static output feedback, multi-objective control (mixed H2/Hinf control problem) is of interest. In classical design methods all specifications and constraints are usually translated into a unique setting and then met through the minimization of a unique performance measure. On the contrary multi-objective control theory offers a very flexible and powerful design framework in which the control engineer can freely select arbitrary performance channels and uncertainty models and choose the most appropriate norm to represent the design specification for each one of these.

Besides PI(D) algorithms predictive control algorithms are also widely applied. Industrial program packages support the practical usage of predictive control. Major recent accomplishments include significant results concerning robust stability of predictive control under linear dynamics. In addition, a number of stability results on the nominal stability of predictive controllers for non-linear systems have appeared mostly in the form of sufficient-only conditions. Although the latter results are deemed to be somewhat conservative from a theoretical viewpoint, they appear to be adequate for practical control designs. Predictive control under constraints can be considered also as a multiparametric programming task where the control inputs are the optimization variables and the states and the reference signals are the parameters. The predictive control law can be computed algorithmically and can be implemented using an off-line calculated look-up table drastically decreasing the computation time.

2.4 Control applications in nonlinear systems

In most control applications (like process control, engines, manufacturing systems, robotics, space systems, etc.) plants contain nonlinearities. Control of nonlinear systems considering the nonlinear characteristics of the system would provide better control performance than applying linear controllers. Different solutions of nonlinear control problems are addressed by the IFAC NOLCOS conferences which attract increasing interest. A recent summary is provided by (C. Bonivento *et al*., 2007). A traditional solution for control of nonlinear systems is gain scheduling, design of controllers in each linearised operation region and switch among the controllers according to the operating point. This solution is limited, as it is restricted to slowly varying operating conditions, there is no guarantee for stability or performance, and computer storage requirements are high.

2.4.1 LPV methods in control of nonlinear systems

Recent major accomplishments in control of nonlinear systems are applying linear parameter-varying (LPV) systems, which use parametrised linear systems to describe the nonlinear system dynamics over the full operating range (K.M. Grigoriadis, 2005, F.Wu and K.M. Grigoriadis, 2001). The parameters are measured in real time. The plant dynamics change depending on the time-varying parameter, which is not known in advance, it is measured in real time. Examples are engine models that depend on engine speed, air mass flow, etc., or vehicle dynamic models which depend on vehicle velocity and steering input. The controller is adapted based on the measured parameter. In this way the nonlinearity of the plant is considered in the control algorithm. Stability and performance is guaranteed for all operating points and all parameter variations. The controller design requires the solution of a family of Linear Matrix Inequalities (LMIs) – which means a convex optimisation problem. Matlab LMI Control Toolbox provides efficient computational solution of LMI problems.

2.4.2 Soft computing methods to characterize nonlinearities

As real systems are generally nonlinear, describing nonlinearities and handling nonlinear characteristics in control systems is an important question. Where analytic description is not available, *soft computing* methods (fuzzy, neural, genetic algorithms) have significantly contributed to the approximating description and identification of nonlinear systems. It is a challenge to give control design methods based on these models.

2.4.3 Multi-model – multi-controllers supervised by logic-based switching

In the presence of nonlinearities, large modelling uncertainties, noise and disturbances, the control of a system can be successfully obtained by means of hierarchical control structures. The control structure consists of a family of candidate controllers supervised by a logic-based switching.

Each candidate controller achieves the required performance as long as parameter uncertainties of the plant range within a fixed region, but if the uncertainties are very large, no single controller can satisfactorily cover the entire range of parameter variations of a poorly modelled process. Therefore, switching between different local controllers (where local here refers to the domain of variation of the uncertain parameters) is needed. The overall control architecture typically consists in a family of controllers (multi-controller), a family of estimators (multi-estimator), a generator of monitoring signals and a switching logic. The task of the switching logic is to generate a switching signal, which determines at each instant of time the candidate controller that has to be placed in the feedback loop. Controller selection is based on the values of monitoring signals. Major theoretical issues in the design of this kind of supervisory control arise from the choice of the switching logic, which determines the overall stability and performance of the resulting closed loop system. Switching control of linear and nonlinear plants has a major impact in industrial-driven problems, especially in the automotive field. Active/semi-active control of suspension, or injection combustion control are only few examples. The relation between state-driven and time-driven switching strategies should be better explored.

Another multi-model approach is when the models are weighted and mixed according to some distribution rule.

2.5 Control – Computation – Communication

Control and Communication are topics that have been widely addressed in recent years. The motivation is integration of heterogeneous collection of physical and information systems. Some applications are power systems, manufacturing, entertainment, etc. Challenges are to ensure reliability and robustness.

Control and Computation are closely related. Computation means Computer Science, which includes "information" and "software". Development of computer science motivates new applications in control. Various computer science topics are receiving attention within control, e.g. computational geometry (tools for vision and robotics), computational complexity (how difficult is a problem?), etc.

Computer science also means algorithms (which are behind software). More emphasis has to be put on the link: Algorithms - Computer science - Control. Algorithms for important control problems provided by modern applications have to be analyzed considering also running time for real time applications (R. Tempo, 2006).

2.6 Robust control of large scale systems

Nowadays more and more systems are becoming distributed, consisting of large number of components of very different nature, which exchange information through wire/wireless networks (wireless communication in the loop).

These systems are called also hybrid systems. A hybrid system can be defined as a set of continuous time systems that interact with discrete event dynamics. Hybrid systems encompass mode switching in adaptive control, air traffic management system, formation flying of multiple air/space vehicles, and reconfigurable control. Within hybrid systems, continuous time systems are typically modelled as either linear or nonlinear systems. On the other hand, discrete event dynamics are modelled as many elements such as dwell-time and simple logics. With these models, the hybrid system is characterized in terms of stability, performance analysis, and worst-case reachable set using various numerical tools such as LMI and dynamic programming. Roughly speaking, an appropriate numerical tool mainly depends on the type of the continuous time systems. (Witherto robust control? Panel discussion, ROCOND 2003, P.J. Antsaklis, 1998.)

Embedded systems working in large scale systems through computer network are becoming common applications which require new robust control methods. Control of networks, control over networks have to consider big model uncertainties, changing time delays, losses of information, etc.

While control, information theory and communication can be considered as mature disciplines, little effort has been put so far in understanding how issues in information theory affect the performance of a distributed control system.

Challenges are design methods for interacting controllers, estimators, communication channels to achieve prescribed performances with minimum loss, high efficiency and with decisions made by a large number of users. Important issues are quantitative analysis of how the performance of the system is affected by bandwidth, changing delays, quantization errors, transmission noise and loss of information. Data handling, control of data flow, conflict resolution, avoidance of deadlocks, resource allocation are also important questions.

Feedback loops with quantization (modelling communication constraints) where quantization error represents the uncertainty have to be also analyzed and designed for robust performance.

“Complexity” demands deeper understanding of the system. Modelling, analysis and control problems of large interconnected dynamical systems with hybrid decision variables have to be analyzed.

Large scale systems, decentralized and distributed control schemes, embedded systems and sensor networks will foster the convergence of control, computing, communication and networking.

Emerging applications areas are distributed manufacturing, remote control and coordination of unmanned vehicles, intelligent traffic control, remote laboratories, remote surgery, etc.

2.6.1 Communication and control of distributed hybrid systems

In the last decade extensive research addressed the description, analysis, controller design, simulation and implementation of distributed systems (T. Simsek, P. Varaiya, J.B. de Souza, 2001). The research has incorporated control concepts as stability, optimality and performance insurance. From the computer-science side, logical specification and verification, event-driven state machine models, concurrent processes and object-oriented approaches have been applied. As an important case study control of an automated highway system has been considered. In networked multi-vehicle systems, information is exchanged among multiple vehicles and the commands consider interactions as well. The aim of the control of this distributed and hierarchical system is to increase highway capacity, safety and efficiency without building more roads. The control system has to consider non-ideal conditions as well, such as noisy communication, sensor and actuator failures, etc. The control methods have to cope also with dynamic reconfigurations.

A new description model of the interdisciplinary hybrid systems has been developed. The distributed hybrid system can be considered as a collection of hybrid automata that interact through the exchange of data and messages.

Additionally, wireless communications research area covers *sensor and actuator networks* that are investigated from the system level point-of-view. Research problems arise from the data management issues, but also coordination of actuators and networked control are considered.

Several results of optimal control, viability theory, differential games, discrete event systems, switched control, logical theories have been used together to describe and solve the problems. Modelling, design and implementation tools have been developed. This is an area of extensive research, which needs new approaches

2.6.2 Time delay systems

Systems with delays frequently appear in engineering. In addition, actuators, sensors and field networks that are involved in feedback loops usually introduce such delays. Time delay systems, frequently considering changing time delay have to be analyzed especially in case of large scale networked control systems (a networked control system refers to a control system whose feedback loop is closed through some network channels). Stability of networked control systems, quality of service in video transmission or high-speed communication networks, teleoperated systems, parallel computation, robotics, etc. are key issues. The presence of delays makes system analysis and control design much more complicated. Key contributions have been made for less conservative results of delay-dependent robust control for retarded/neutral systems. Generally, neutral systems find abundant applications as propagation and diffusion, and in approximations of infinite-dimensional distributed systems.

2.7 Multiobjective design via Q-parametrization

Control system design problems are invariably multi-objective, as there are several, usually competing requirements that need to be satisfied.

For flight control systems the problem is often formulated as a multi-objective one, since it can be very costly if one fails to get the necessary trade-off between the competing objectives of performance, robustness, actuator effort, controller simplicity etc. Consequently, there have been many multi-objective design approaches proposed, (e.g. J. F. Whidborne *et al*., 1994; C. Scherer *et al*., 1997). An important development in multi-objective control design was the realization that many performance indices are convex in nature (E. Polak and S.E. Salcudean, 1989; S. Boyd *et al*., 1990). Furthermore, using the *Q*-parametrization (or Youla parametrization) the performance indices are convex with respect to the free parameter *Q*. This approach is now being utilized for practical applications, particularly in the flight control area (O. Cifdaloz *et al*. (2003); O. Voinot *et al*. (2003); G. Ferreres and G. Puyou (2006)). The closely related convex combination method reduces the problem to a linear programming problem, and has resulted in some applications (e.g. K. Fu and J.K. Mills (2005)).

2.8 Dynamic control systems under uncertainty

Many problems originated in engineering, ecology, medicine, social sciences, etc. are characterized by the presence of some factors introducing uncertainty into behaviour of control systems. Especially important are the systems which are given by multidimensional differential equations or by differential equations in an infinite dimensional space due to their significance in modelling real phenomena. Very often probabilistic characteristics for uncertainties are unknown, only restrictions on these uncertainties are known, as a rule. In such cases it is convenient to formulate the problem on the basis of the concept of guaranteed control. The guaranteed approach to solution of control problems with uncertainty comes to be more and more popular. This approach can be used not only for game control problems, but also for estimation, guaranteed identification and reconstruction of dynamic systems. An approach based on the idea of guaranteed control provides a unified solution of these problems using the method of N.N. Krasovskii *et al*. (1988, 1995) in differential game theory as a main tool. The kernel of the methodology is the positional principle of extremal shift of the control system to a stable (invariant in a certain sense) manifold in the space of positions of the control system. The assumption about the character of information available plays an important role. For game control problems with incomplete information and for estimation problems a position is an information set or an information state; for control problems of systems with hereditary information a position is a preceding part of the phase trajectory (A.B. Kurzhanskii, 2004, N.N. Krasovskii and N.Yu. Lukoyanov (2000)). The positional approach to problems of guaranteed control fits well in the framework of the evolution of general control theory. On the one hand, it is closely linked to the optimality principle and to the methodology of dynamic programming. On the other hand, it is closely connected with the concept of invariance.

A scheme for construction of positional control utilizing the extremal shift approach includes two basic stages. On the first, preparatory stage, which can be realized in advance, one constructs a stable manifold guiding to the target set. On the second stage, a positional extremal control is constructed using the condition of extremal shift of the control system to the stable manifold.

In the case of control systems acting in the absence of uncertainty the problem of constructing a stable manifold degenerates to the problem of finding controllability sets.

In theoretical research one should base on adequate constructions of the modern non-smooth and convex analysis for description of stable manifolds and value functions. Sufficiently effective tools have been developed for analysis of stability properties, and the results clarifying the structure of solutions in problems of optimal guaranteed control have been obtained. In the field more oriented on calculations, it should be admitted that the unique real way is to develop numerical methods and algorithms of approximate calculations based on using the technique developed in the theory of non-smooth analysis.

The following problems from this class could be mentioned: problem of guaranteed control with phase restrictions, game problem of approach, problems of viability, time optimal control, etc. For these classes of problems algorithms and programs for low dimensional control systems have been created. Simulations for a number of problems of flight mechanics, dynamics and ecology have been realized. The developed methods are used for solving various problems of economics as well. Development of algorithms and programs for multi-dimensional control problems is restrained, mainly by the limited capacities of computers. Among the developed algorithms for constructing stable manifolds and value functions one can give accent to grid methods and related pixel methods (S.V. Grigor'eva *et al*., 2000). Grid methods are based on local convexification of sets or functions and use constructions of sub-differentials and quasi-differentials. While the grid methods are rather analytical and closely connected with calculation of values of the Hamiltonian of the system, the pixel methods have geometrical nature. They are straightforward under multiple realizations of operations of union and intersection of sets, which are typical for problems of guaranteed control.

The vitality of approaches and constructions created in the positional differential games theory is demonstrated not only by the fact that they allow to cover non-regular problems of control theory which have non-smooth solutions, but also that they have been extended to other spheres of science. For example, these approaches and constructions have been extended by A.I. Subbotin (1995) to analysis of wide classes of first-order partial differential equations in the form of minimax solutions. This theory originated from non-smooth analysis harmonizes with another theory of generalized solutions of partial differential equations, namely the theory of viscosity solution (M. G. Crandall and P.L. Lions, 1983) whose sources lie in ideas connected closely with differentiability of functions. As a demonstrating example a motion of airplane in a horizontal plane is considered. The problem is to reconstruct the airplane trajectory on the basis of the set of inaccurate measurements for its geometrical state under known restrictions for measurement errors. The solving algorithm (V.S. Patsko *et al*., 2005) uses the ideology of informational sets. In Fig. 4 the polygons present uncertainty measurement sets, and their shaded parts present informational sets. The real airplane trajectory is shown by the red line and the reconstructed trajectory is shown by the proper line.

2.9 Use of image and speech processing, computational vision in intelligent control

Trajectory optimization of moving objects under changing environment, learning in 2D, 3D space is an important task in robot control. Going out from one dimension to 2D and 3D gives a number of tasks to be solved. New effective real-time optimal algorithms are needed for 2D and 3D pattern recognition. More complex sensing and signal processing have to be used. Algorithms for image processing and computer vision are given by J.R. Parker (1997).

2.10 Operation and maintenance, fault detection

Monitoring the performance of an industrial process or of a machine is usually of great interest to the owner, since maximizing performance usually maximizes also quality and income. Different types of performance measures can be constructed. Their basic use is in monitoring, but this can be extended to condition monitoring and fault diagnosis in order to find the causes of poor performance as well as components that need maintenance.

Fault detection and condition monitoring methods are usually divided into three main categories: model-based, knowledge-based and data-driven systems. In model-based methods a mathematical model (often a differential equation system) is built for the monitored system from physical principles and

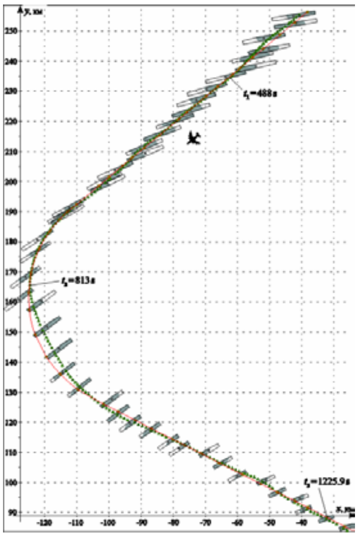

Fig. 4. Airplane trajectory

the predictions given by this model are compared with the actual measurements from the system to detect faults. The main limitation with this approach is that many systems are too complex to allow any sufficiently accurate model to be built. Often fault situations are handled by ad-hoc procedures developed by human experts. Knowledge-based methods (e.g. expert systems, fuzzy logic) try to automate the use of this knowledge. The problem with these methods is that it is time consuming to gather the knowledge from the experts and to maintain the database as products evolve. Data-driven methods try to deduce the properties of the system more or less directly from the available measurement data, which are usually readily available in modern industrial plants.

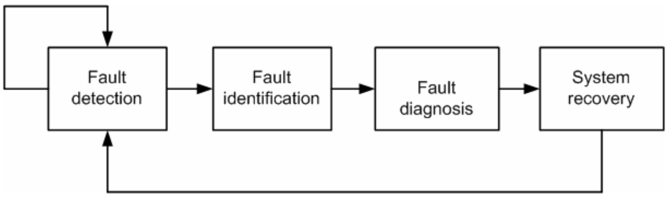

Fig.5. Process monitoring loop

Fig. 5. represents a complete process monitoring loop. During normal operation a fault detection system monitors the process for possible faults. If a fault is detected, the affected measurement signals are isolated in fault identification. Then the exact location, magnitude, and time of the fault are found out during the fault diagnosis phase. The corrective actions that return the system to its normal operating state are then performed (system recovery).

2.11 Bioinformatics and Neuroinformatics

Systems biology aims to model the complex interaction among gene expressions and protein metabolism.

Biological systems which have been experimentally verified to be robust to significant changes in their environments require mathematical models. Based on these models hybrid optimization methods could be worked out, using genetic algorithms and other biological disciplines together with sequential quadratic programming to find the global optimum with tolerable computation time.

On the other hand, neuroinformatics aims to model the complex behaviour of the natural neural network. The nervous system is probably the most complex existing information and control network. In the human brain million of billions of bits for each second are elaborated through complex neural circuits. The nervous circuits are constituted by neurons communicating in a neural pathway across the synapses.

Although a number of biological properties of such circuits have been already studied, the process of elaboration and transmission taking place in a synapse is not completely clear. In this context, the expertises covered by the area of modelling and control could be of great benefit. Fig. 6 (taken from Baraldi *et al.*, 2007) shows the activity of the cells of the cerebral cortex under a voluntary move, obtained by an identification procedure, through filtering a magnetic functional resonance signal.

One of the most interesting problem concerns the cellular network of the brain, which is naturally involved in the sensor-motion and emotional knowledge-based control.

The neural network is composed by an input stage, constituted by about one million of billions of granular cells and by the so-called Golgi cells that generate a complex inhibition process through a negative feedback loop. In such a circuit loop the possibility of learning and memory has been proven. Given its known structure, it represents a real basis in order to explore the elaboration of the neural code.

Three interactive directions appear soon as promising:

1) Development of mathematical models for the activation of the single neurons. Thanks to these models it will be possible to reconstruct the electrical field out of the cells and the signals measured during specific behaviours, like emotion, pain, etc.

2) Based on the development of a neural cell the electrical behaviour of the single neuron of the cell is reconstructed. A prototype constituted by about 10000 neurons satisfactorily represents a real situation.

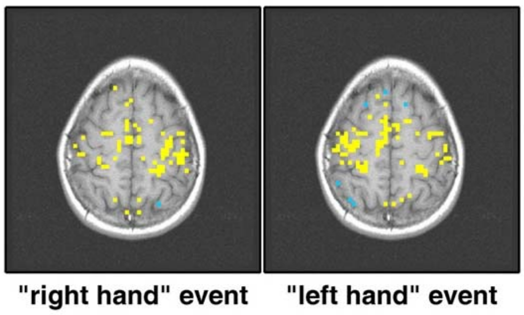

Fig. 6 Activity of the cortical cells

3) Development of appropriate algorithms for the convolution/deconvolution of the signals. At this regard,

quite interesting is the functioning of the granular stratus of the cerebellum, which exemplifies the case where (a) the cellular elements of the network are homogeneous (G. De Nicolao and Liberati, 1993, G.P. Drago *et al*., 2002), (b) the activity of the single elements cannot be individually measured as would be necessary for the analysis of the coding properties. As a consequence, the multi-compartmental modelling of the granular cell is of great importance. Firstly, this permits the simulation of the convolution of different time-phases signals in order to reconstruct the extra-cellular potentials field during the absorption of electrical isotropy in the network; secondly, different combinations of synaptic activities can be studied in order to find the correlation with respect to the granular stratus input.

A number of important problems are:

a) Deconvolution inverse problem, useful for estimate the source, given a noisy measurement of the signal and an approximated knowledge of the transmission channel;

b) Nonlinear modelling, as in the case of the cancer growth;

c) The synchronization or coherence grade both partial and nonlinear between correlated signals, and the estimate of the information propagation direction;

d) The separation of the signal from the noise provided a model of both signals is obtained.

Bioinformatics, biosensors provide new application fields. On the other side, understanding better biological systems and biological societies (*biomimetics*) would lead to optimization algorithms which could be used effectively in technical systems.

2.12 Cybernetic systems

A new approach to investigate complex systems is called *neocybernetics*. Cybernetic systems are complex systems with “emergent” behaviours. They are characterized by mutual interactions and feedbacks among lower-level actors, resulting in dynamic structures. The emergence in such systems is manifested as *self-organization* and *self-regulation*.

The key point in neocybernetics is that the *emergent models* are studied directly rather than the physical first-principles models. It turns out that the analysis and synthesis tools are based on *multivariate statistical methods*. It has been assumed that behaviours in complex systems cannot be analyzed using traditional mathematics: deeply nonlinear and chaotic models are needed. However, when directly concentrating on the final patterns, one can trust on *linearity* and *stability*. Rather than studying the hopelessly complex nonlinear iterations at the edge of chaos - the mainstream approach today - much broader views can be seen around the dynamic equilibriums. It turns out that cybernetic systems are based on *higher-order balances*. It is *control theory* that offers the conceptual tools for understanding the behaviours in nature: *A cybernetic system implements model-based control of its environment*.

2.13 Microsystems and nanotechnology research

The research focuses on *micro/nano robotics*, *micro/nano manipulation*, *and microfluidics* as well as on the *control of active materials*. The emphasis is on the system level, including system analysis and design along with feedback control and automation. Applications are in the fields of electronics assembly, papermaking, biomedical technology and material science. Micromanipulation and micro assembly are important technologies in the handling and assembly of very small microelectronic, micro optoelectronic, micromechanical and micromechatronic components.

Modelling of micro and nano objects is of interest, and application of the models in physics-based virtual reality simulation helps in control design. In *cell and molecular biology*, a single cell technology is being developed to provide novel tools for toxicologists, drug developers, and HIV and cancer researchers. The core of expertise is the automation of single cell injection, isolation and cellular measurements using micro robotic techniques. The research in nanotechnology focuses on *nanorobotics* and its applications in material science. The research topics include nanomanipulation, measurement of nano forces, environmental influences on nano forces and nanohandling models.

3. NUMERICAL ISSUES

3.1 Effectiveness of LMI optimization application to real synthesis and analysis problems

In recent years *Linear Matrix Inequality* (LMI) techniques have become quite popular in control design. The main reason for this popularity has been the discovery of interior point methods for convex programming that allow for the numerical solution of LMI’s in shorter time. It has been acknowledged that many control problems can be formulated in terms of LMI’s, but only the *interior point methods* have rendered these formulations attractive from a computational point of view. LMI’s can efficiently deal with multi-objective design problems, in which synthesis of a controller is desired that simultaneously satisfies different performance objectives and/or constraints on different input/output channels of the controlled plant. The prominent role of LMI’s as the central computational tool within the area of robust control has been confirmed by a large activity on broadening the scope of existing techniques. In numerical computation, dedicated *public-domain* LMI *solvers* have been developed for control design problems with Kalman-Yakubovich-Popov structure, such as the characterization of positive-realness in signal processing applications or for robustness analysis on the basis of integral quadratic constraints. Moreover, first publicly available general-purpose BMI solvers are emerging. Most importantly, all these software packages are interfaced with YALMIP (yet another LMI parser) for a very user-friendly common access, and they are complemented by COMPLIB, a comprehensive database of linear control design problems in state-space format. Recent achievements include the hierarchy of LMI relaxations to solve non-convex optimisation problems with polynomial objective functions and constraints, based on the theory of moments and its dual sum-of-squares decomposition in algebraic geometry and as implemented in the complementary Matlab software GloptiPoly and Sostools both released in 2002. Applications are in fixed-order controller design, robustness analysis, nonlinear system analysis and design. Mixed integer optimisation programming methods are also available.

3.2 Randomized algorithms

A new type of randomized algorithms, the so called Las Vegas algorithm has been introduced (R. Tempo and H. Ishii, 2007), which always gives the correct answer. The only difference from one run to another is the running time. These algorithms provide a link between randomized algorithms for uncertain systems (of Monte Carlo type) and the area of multi-agent, cooperative and consensus control (R. Tempo *et al*. 2005).

3.3 Matlab toolbox on periodic polynomial manipulations

The polynomial approach to periodic control has been investigated. In particular, *the parametrization of all stabilizing controllers has been extended and used for the solution of typical design problems*. Also, a Matlab toolbox on periodic polynomial manipulations has been realized.

3.4 Robust numerical methods for robust control

Recently there are some attempts to find numerical methods for robust control problem of dynamic systems using orthogonal functions like wavelets, Walsh functions, block pulse functions, Laguerre polynomials, Legendre polynomials, Chebyshev functions and Fourier series. The main characteristic of these techniques is that it reduces these problems to those of solving a system of algebraic equations for the solution of problems described by differential equations, such as analysis of LTI systems, singularly perturbed systems, second order systems, time-varying systems, model reduction, optimal control and system identification. Thus, the solution, identification and optimization procedure are either greatly reduced or much simplified accordingly.

4. SOME APPLICATIONS

New control theories and techniques in a lot of cases are initiated by real control demands. On the other hand new theories and techniques find new application fields. In the sequel some applications are listed.

With a delay of about ten years, theoretically well-established *robust control techniques are now finding dissemination in industrial practice,* e.g. within production technology, automotive and aerospace control. In automotive industry, increasingly strict pollution restrictions dictate more precise control of combustion, which requires application of nonlinear and robust control methods.

4.1 Robust control techniques applied to aerospace systems (robust generic and integrated systems of satellites coupling attitude control and orbit control). In particular, formation *flight is a particular trend with accuracy requirements and autonomous orbit control.*

4.2 Recently developed *linear matrix inequality based robust estimation techniques have found their way into integrated navigation systems* since inertial sensor errors (in gyroscopes and accelerometers) and the errors due to navigation systems (GPS, radar, barometer) can be more accurately modelled within a worst-case framework as opposed to being considered as coloured noise. Moreover, mismatches caused by linearization can be treated as unmodelled dynamics, while still providing guaranteed bounds on the estimation error variance.

4.3 Guaranteed robust analysis versus Monte-Carlo techniques (that are used in the validation process by aerospace industry) for the validation of the control laws.

4.4 Adaptive optics. The idea is to apply robust control theory for the control of the shape of the secondary mirror via piezo actuators in telescopes. Up to now, control techniques that have been used are quasi-static control laws (Kalman filtering with pseudo-inversion of the influence matrix), but for very large telescopes, the dynamics of the mirror has also to be considered. Robust control loop based on a PDE model of the mirror is under development.

4.5 Communication networks. Time delay uncertainty among the sensors, actuators and controllers is a key problem in communication networks. Generally, in this application a delay-dependent robust controller is thought to meet the networked time-delayed environment by using the time-delayed system control theory.

4.6 Power systems. Recently developed robust decentralized controllers have found their way into interconnected power systems under large changes in real and reactive loads that cause large structural changes in the system model.

4.7 Magnetostrictive transducers. This includes development of robust control designs for high-performance smart material transducers operating in nonlinear and hysteretic regimes.

4.8 Engine control. Robust active control has become the standard methodology to control the plant. Due to legal requirements and customer requests, control of engine processes has become one of the key issues in the engineering of automotive drives. For instance, a challenging feature is the fact that almost all processes to be controlled show nonlinear dynamics. Most processes depend on engine speed and the air mass flow rate through the cylinders. In general, gain scheduling approach involves a tedious and time consuming trial-and-error procedure, where the design of local controllers on one hand and the assessment of the overall closed-loop behaviour are separated. In contrast, robust LPV controller synthesis is a one-step procedure, which determines a controller for a predefined parameter set that is automatically adapted to the current operation point. In addition, this technique is comparably easy to tune, because the underlying loop-shaping approach allows defining requirements on closed loop bandwidth, steady state error and disturbance rejection.

4.9 Predictive control has numerous industrial applications. Model predictive control (MPC) techniques are widely used in industrial applications (S.J. Qin and T.A. Badgewell, 2003). The reason is in the flexibility to tackle control tasks characterized by a variety of technological constraints, including those that can be translated in hard bounds on the state and control variables. There are several commercial software packages and companies on the market, which offer services in this area. On the other hand, hierarchical and distributed control is becoming important in many real-life problems, including distributed energy production, energy distribution, control of airports or seaports, etc. A challenge is to adopt MPC techniques and devise scalable algorithms for the control of complex systems where various players act at different hierarchical levels.

4.10 Control of smart structures is a particularly interesting application area. These include flow control, vibration attenuation or precision positioning by using smart material actuators such as piezoelectric patches and shape memory alloy wires. Such flexible structures can be modelled as distributed parameter systems. The inherent properties of smart materials, such as the large number of inputs and outputs or hysteretic effects can be incorporated into the controller design process.

5. FORECASTS

Although many design methods previously considered to be quite "theoretical" are now being successfully implemented in practical applications, there are still many challenges as has been discussed in previous sections of this report. This final section forecasts some of the developments that are expected within the next few years.

New developments in the technology of sensors and actuators will continue to fertilize new control application fields besides the process industries e.g. medicine, biology, crystallography, optical communications and nanotechnology. *All these fields need new efforts for modelling, analysis and design.* More effective usage of data is expected to combine available measured data with first principle models. The data-centric turn has been accelerated by the progress in sensor and data storage technologies. New disciplines – data mining and knowledge discovery from data will be used widely to get usable information. A renewed interest is expected in areas as machine learning, statistical estimation and system identification. Relations of data with dynamics and feedback have to be analyzed. Data extracted from the process will be used to control the process with so-called data driven control approaches which are to be used together with model approaches.

Effective nonlinear control algorithms are to be developed and applied. Nonlinear stability concepts are needed whenever global or semi-global properties are of interest, e.g. for analysis of global convergence and attraction behaviour, or investigating robustness under perturbations. A major challenge is the stability analysis of large non-linear networks. Interplay between theory and computational techniques is crucial, as analytical and algebraic methods are often impractical for complex systems, and many numerical techniques are feasible only in low dimensions. There is a need for control-relevant non-linearity measures to decide whether linear or non-linear control is required.

New effective real-time optimal algorithms are likely to be developed for 2D and 3D pattern recognition in cases where more complex sensing and signal processing is used e.g. for 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 involving an extremely large number of control loops, coordination of large number of autonomous agents, to control hybrid and stochastic systems and to handle very large model uncertainties. For example a distributed hybrid system is a networked multi-vehicle system, where information and commands are exchanged among multiple vehicles, and the relative positions, dependencies change during operation. Another important example is given by supply chains of production units, where flows of materials and information must be controlled in spite of stochastic market demand, production constraints and transmission delays.

Robust control of large-scale systems raises important questions, and significant advances are expected. Control of networks, navigating packages from sources to destinations on a very large scale heterogeneous communication network (such as the Internet, web applications) with minimum loss, high efficiency and with decisions made by a large number of users in a distributed fashion are typical examples. The effect of varying transport delay time will be considered, and solutions are expected.

Control over networks will become an even more important application area. Embedded digital devices that interact with the surrounding world via sensors and actuators which are widely distributed and linked via communication networks and whose actions are coordinated according to some specific control goal are expected to be widely used in industrial applications. Examples of such networked control systems have appeared in manufacturing plants, aircraft and traffic control.

Control design of hybrid dynamic systems raises important tasks. Hybrid dynamic systems consist of continuous plants, sampled-data controllers and switching logic supervising the system considering signal ranges, sensor failures, etc. Performance analysis and design, simulation and verification of operation will be addressed for these types of applications.

Distributed hybrid control systems involving extremely large number of interacting control loops, coordinating large numbers of autonomous agents, handling very large model uncertainties (as e.g. the networked multi-vehicle system) will be in the centre of future research. Dynamic game approaches will also facilitate the analysis and control of such systems.

Telecontrol, control via the network opens new vistas for diagnostics, telesurgery, distance education, etc.

Utilization of renewable energy sources will gain significantly more applications. As one of the consequences, the number of small size dispersed power plants will increase. There is a need for new control concepts to handle control problems arising in this environment.

New applications for controller design will come by the use of *micromanipulators in biological systems*. *New achievements in bioinformatics* will make it possible to develop new artificial sensory organs e.g. for vision, smell, hearing. These new developments will open many new dimensions for control.

Artificial intelligence, learning algorithms used *in robot control*, *intelligence built in mechanical systems* will provide more clever and self-sufficing robot assistance for people in production and in everyday life. In the area of home automation, in particular, intelligent appliances and devices, besides simplifying mundane tasks for humans, will help in saving energy and resources like water and gas. Development of intelligent robots which imitate the movement of different animals will bring new possibilities for intelligent control applications in unknown or dangerous environment. Intelligent control of complex distributed systems with moving and cooperating objects could be realized with Intelligent Space with ubiquitous sensory intelligence. Cognitive vision, description of behaviour based on cognitive knowledge gains significant emphasis.

In neuroscience a further direction is in the possibility of directly elaborate the brain signals underlying the intention towards the so-called Brain Computer Interfacing, helping the direct control of the actuators without muscular intermediation. An important sub-product can be envisaged, concerning the development of artificial neural networks which are closer to the physiological reality.

Currently adopted neural networks are strongly limited by the simplifying assumptions on their structure and the functions of their neuronal elements. Therefore their efficiency is somehow reduced. A bottom-up and reverse engineering technique can be proposed in order to estimate the activity of the neural network of the cerebellum, starting from its cellular and synaptic elements, defined at a detailed biophysical level. The network will be shaped coherently with experimental morphological-functional data. Moreover, it will be equipped with complex space temporal dynamics and non supervised learning rules. Besides its obvious importance for the comprehension of the information elaboration in the nervous system, such an analysis paves the way to a number of applications, for instance in the modelling of neural circuits for robots that imitate the perceptive properties of living organisms.

Virtual reality is developing at a very impressive rate. For example, it is used in simulators for aeroplanes and is going to be used in teaching of automobile driving or in traffic control and in a lot of other applications. In consumer electronics virtual reality plays an increasing role. The implementation of virtual reality requires computer science for creating a virtual world (using image processing for instance), modelling of human perception and developing appropriate man-machine interfaces.

Specific technologies and complex systems will set new quality requirements and new challenges for control systems. Such complex systems include multi- agent distributed communication systems, mass production in the automotive industry, in consumer electronics, in microelectronics, control of environmental protection technologies, control of production of renewing energy resources, etc.

In the field of *optimal control under uncertainty* the method of extremal shift and other methods created in the framework of the positional approach will be applied to new classes of problems of control and dynamic inversion problems. Some variants of the method will be developed for problems of guaranteed result with heredity, for problems under lack of information for nonlinear distributed parameter systems. In connection with increasing growing deficiency of earth resources, great attention will be given to problems of guaranteed control with phase constraints, in particular, to various problems of viability of control systems. Special constructional algorithms of regularization based on the method of the regularized extremal shift will be suggested for solution of dynamic inverse problems. Some economical and ecological problems will be considered as applications. Construction of solvability sets in guaranteed control problems on the basis of results of incomplete observations is a direction of future research.

All these areas provide big challenges for control research.

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