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DESIGN METHODS

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1. CURRENT STATUS

1.1 *Introduction*

Automatic control deals with the development and the implementation of methods leading to automatic decision processes, for the purpose of improving the performance of industrial, biological, socio-economical systems. The basic principle of automatic control is feedback: information on the state of a system is collected (sensors) and actions on a system is exerted (actuators) so as to influence its behaviour. In between, the central task is the conception and the implementation of control laws and algorithms. As a consequence, the evolution of control theory and practice is closely related to the evolution of the technology of sensors, actuators and devices for the real-time implementation of decision and control strategies.

The main advances in the last years in control design have been concerned with a deeper understanding of the robustness issues and the development of new tools and models to cope with uncertainty. Such progresses in theory have made it possible to improve the performance and safety of certain complex systems such as for example automobiles, unmanned underwater vehicles, high-performance aircrafts, etc. In the meanwhile, the so-called "soft techniques" such as fuzzy or neural network design have been introduced, to take into account modeling factors that cannot be considered directly within a standard mathematical framework. However, new theory is still needed in order to be able to handle highly complex systems such as those involving an extremely large number of control loops, or the coordination of a large number of autonomous agents, to control hybrid and stochastic systems and to handle very large model uncertainties.

New developments in the technology of sensors and actuators will open the door to new application fields such as medicine, biology, crystallography, optical communication, nanotechnology, for control methods. All these fields need now new efforts for modeling, analysis and design. Also, improvements in microprocessor technology will make it possible to apply more sophisticated and more powerful algorithms for control that include fault tolerance capacity. In fact, computers, real time implementation and telecommunications are closely related areas in which complexity, reliability and safety requirements are integrated.

1.2 *Key problems addressed within this field*

Control design is obviously a rather broad topic and not one particular technology. As control is ubiquitous and indispensable in all technical systems except very simple mechanical or electrical ones, so is control design. If there is feedback or dynamic feedforward, it has to be designed somehow. Thus control design is and will always be an important area for almost all technologies.

It is also well-known and accepted as a matter of fact also by control theorists that a large number of feedback control problems can be handled reasonably well by relatively simple, linear controllers, namely of P/PI/PID-type. In industrial plants, many of these controllers are tuned on-site by technicians or even only set once at the commissioning of the plant. The tuning of simple controllers under the assumption that a faithful linear plant model is available has been dealt with in a large number papers at conferences and in journals for several decades. A recent IFAC workshop on the topic of PID-control attracted a remarkably large number of participants. Significant research and development work in this area has been performed on auto-tuning algorithms for standard controllers and such algorithms are now offered by many vendors of industrial control systems. While control research has moved on far beyond the tuning of PID controllers, the conservation of the knowledge on basic issues in SISO controller tuning and its compilation into authoritative books or web-based teaching material is still necessary. An important aspect here is the knowledge on the limits of controller performance which has mostly been gained in the early 80s. It provides fundamental insights into the benefits and the limitations of feedback control.

Linear controller design becomes a nontrivial issue as soon as systems with several inputs and outputs and interactions have to be controlled. Both the selection of the best control structure, i.e. the decision which inputs and outputs are used for control and how they are used in the controller (loop pairing, fully or partly multivariable controllers) and the tuning of multivariable controllers in practice pose challenging problems. Reliable methods for control structure selection are still an open research issue.

In the process industries, linear model-predictive control (MPC) has become the standard technology to control multivariable plants. There are several commercial software packages and companies on the market which offer services in this area. The main advantage of this technology over standard linear controller design techniques is the ability to handle constraints on the inputs and outputs of the plant. Thus the available range of the actuators is used fully. The development of algorithms which can guarantee closed-loop stability for MPC controllers with constraints was a major research achievement, however commerical packages usually ignore this issue completely. The main effort in industrial MPC projects is spent for the identification of linear models of sufficient accuracy from plant experiments. Tuning of MPC controllers also can be tedious, as a large number of parameters can be chosen, e.g. length of control and prediction horizon, weights on the inputs and on the controlled variables, filter constants. It might be promising to use more of the available knowledge on linear multivariable control in this process.

A number of successful industrial applications of nonlinear model-based predictive control has also been reported. Due to the considerable effort which is necessary to obtain sufficiently accurate models from first principles, this at the moment is a technology for hard problems of special importance, e.g. in polymerization processes where the dynamics change considerably over the batch run.

As the derivation of first principles models is time consuming and often not possible, there is a considerable interest in the use of nonlinear black-box models in model-based control schemes, e.g. neural networks. There has been a lot of academic work in this area, but industrial applications are rare because of the issue of the reliability of such models in situations which have not been represented well in the training data and the need of supervision that prevents that the models are used in a range where they had not been trained.

In many areas, there is a clear tendency towards high-performance controllers, e.g. in cars, airplanes, audio equipment, motors, steel-forming plants. In these application domains, often complex rigorous and faithful models are available either because they have been developed for design purposes or because the commercial importance of high-quality control justifies this effort. Nonlinear controllers, mostly based upon exact feedback linearization are increasingly applied, complemented by process specific transformations feedforward paths etc.

Fuzzy control attained a lot of attention in industry and in parts of academia some years ago, but this has decreased considerably. The experiences are that this is a technology which can mainly be used in two ways: to generate a simple nonlinear controller that somehow solves the problem for not too high performance specifications on a purely try-and-error basis (low cost and low performance), or to integrate available qualitative knowledge about the influence of additional known or measurable quantities in a control scheme which otherwise is difficult because of the lack of a quantitative mathematical model of the interactions.

1.3 *Some recent major theoretical accomplishments*

In recent years, *Linear Matrix Inequality* (LMI) techniques have become quite popular in control design. The main thrust to this popularity has been provided by the discovery of interior point methods for convex programming that allow for the numerical solution of LMIs in polynomial time. It has been quite sometime that it was acknowledged that many control problems can be formulated in terms of LMIs, but only the interior point methods have rendered these formulations attractive from a computational point of view. LMIs can efficiently deal with multi-objective design problems, in which the synthesis of a controller that simultaneously satisfies different performance objectives and/or constraints on different input/output channels of the controlled plant is sought. While in classical design methods all specifications and constraint are usually translated into a unique setting and then met through the minimization of a unique performance measure, 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. Another feature of the LMI-based design techniques is the so-called Linear Parametrically Varying (LPV) approach to gain-scheduling, in which gain-scheduled controllers can be systematically designed with theoretical guarantees for stability and performance, avoiding the troublesome interpolation step that is typical of classical gain-scheduling.

In the presence of large modeling uncertainties, noise and disturbances, the control of a system can be successfully obtained by means of hierarchical control structures. Typically, a two-level control structure of this kind consists of a family of candidate controllers *supervised by a logic-based switching*. Each candidate controller achieves the required performance so 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 modeled process. Therefore, switching between different local controllers (where local here refers to the domain of variation of the uncertain parameters) is needed. Such switching schemes are an appealing alternative to the traditional continuously tuned adaptive controllers in several respects. Indeed, scheduling the controller on the basis of a partition of the region of admissible values of plant uncertainties reduces the conservatism and hence improves the performance; moreover, transients in the adaptation process can be more efficiently handled. The overall control architecture typically consists of 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, which are obtained by taking integral norms of suitably defined estimation errors produced by the multi estimator. Major theoretical issues in the design of this kind of supervisory control arise from the choice of the switching logic, which indeed determines the overall stability and performance of the resulting closed-loop system. The latter, in fact, is a *hybrid system*, in which the discrete dynamics associated with the switching logic and the continuous dynamics associated with the rest of the plant are combined.

Renewed attention on Lyapunov methods has fostered major advances in the long-standing problem of achieving, via feedback, stability in-the-large in systems modeled by nonlinear differential equations. The notion of *input-to-state stability*, a broad concept that incorporates and extends to the case of systems driven by bounded inputs the classical approach of Lyapunov to the analysis of the stability of motion, has laid the basis for a new body of results dealing with analysis and design of nonlinear feedback stabilizers. By means of systematic recursive methods now known as *backstepping* and *forwarding*, it has become possible to stabilize, robustly stabilize and even adaptively stabilize classes of nonlinear systems possessing a special kind of "triangular structure". The notion of input-to-state stability lends itself to the evaluation, by means of tests that extend in a very natural way the classical criterion of Lyapunov for stability, of a *nonlinear gain function*, by means of which the classical principle of the small-gain can extended in a rather convenient way to analyze the stability of a feedback interconnection of nonlinear systems. As a byproduct, similar to the case of linear systems, this has opened the way to the possibility of robustly stabilizing a nonlinear system in the presence of unstructured uncertainties. The special feature of a nonlinear gain function can be particularly appreciated in the case of a system driven by saturating actuators, where the use of nonlinear (actually, saturated) gain function may lead to sensibly less conservative stability results. The possibility of (globally) stabilizing systems by means of saturated control laws has also been widely investigated as a subject of its own, and systematic recursive methods are now available, for the design of feedback laws, consisting of *nested saturation functions*, that globally stabilize relevant families of nonlinear systems.

The extension of the *internal model principle* to nonlinear systems has lead to the development of a theory of nonlinear servomechanisms, and to systematic design of feedback laws for asymptotic tracking/rejection of fixed classes of exogenous inputs. Recent progresses in this field have shown that, in addition to the well-known robustness properties of an internal-model-based control loop, the need of an accurate model of the exogenous inputs in no longer an issue, as nonlinear adaptive mechanisms can be incorporated in the design, so as to achieve autonomous tuning of the parameters of the internal model.

In the area of *optimal control*, new reliable and numerically robust optimization algorithms have been proposed. With the enhanced performances of the new generation of microprocessors, such algorithms can run in real time and thus offer a better reliability. Also, new simulation tools have introduced, some of which based in fact on optimization methods. Such tools are powerful but a standardization is needed, so as to offer a "unified" or a systematic procedure for analysis and design of complex systems.

1.4 *Relevance to applications of recent advances in control theory*

In *areonautical industry*, the use of high angle maneuvers and thrust vector control means that nonlinear aerodynamic phenomena increase in importance. Appropriate care of saturation phenomena is essential in the control of unstable aircraft. In these design problems, nonlinear control techniques, notably those based on exact linearization, backstepping and nested saturations, are finding increasing application. Techniques based on the synthesis of flat outputs have been also successfully employed in path planning.

In *car industry*, increasingly strict pollution restrictions dictate more precise control of combustion. This requires nonlinear descriptions in terms of so-called motor maps. Another emerging control area concerns anti-spin and anti-skid systems. The tire-road dynamics is highly nonlinear and uncertain: this is an area in which methods of robust control and nonlinear control have contributed to impressive achievements and continue to grow in importance.

In *power systems*, the use of power electronics makes it possible to introduce active stabilization. Many nonlinear design techniques, such as backstepping, passivity based control, exact linearization, synthesis of flat outputs, input-to-state stability have become relevant.

In *telecommunication industry*, the increasing use of new advanced modulation techniques makes it necessary to use power amplifiers with very high nonlinearity. This is accomplished by using negative feedback or by using nonlinear precompensators. This is an area where it is important to use nonlinear design theory. Another important area of application is in the power control and power assignment for cellular phone transmitters.

In *robotics industry*, increasing performance requirements mean that nonlinear effects become more pronounced. A classical problem in this area and in the control of mechanical systems in general is the compensation of friction. A great difficulty here lies in the modeling of friction phenomena. Many of the models used do not capture all aspects of the phenomenon and hence robust nonlinear controllers are of primary importance.

In *consumer electronics industry*, the use of robust and nonlinear control methods for the design of tracking and focus loop in optical data storage devices (such as new generation CDs or DVDs) can guarantee high performance levels through more advanced control design, which would allow cost reduction in the actual manufacturing of the device itself.

Techniques for active *suppression of periodic disturbances* are becoming more and more popular. Here, the theory of nonlinear servomechanisms and in particular the possibility of designing adaptive internal-models provide a powerful conceptual tool of great practical relevance.

2. FORECASTS

2.1 *Needs, challenges, opportunities*

A broad area in which theoretical advances, in many different directions, are expected is the control of *large complex systems*. A first major issue here is that of model reduction, which is of paramount importance in case the system is so large that several million state variables are needed for its description. Need for applications of this kind method abound: weather prediction, design of very large scale integrated (VLSI) devices, chemical vapor deposition (CVP) reactors, etc. The key challenge here is the development of model-reduction methodologies which are numerically reliable and applicable to very large problems; at the same time these methodologies must satisfy system-theoretic constraints, e.g. preserve stability and have explicit error bounds. Large complex systems are also the biological systems, in which exciting applications of control design are to be expected, as related to the rapidly growing understanding of the control mechanisms which control the development of cells.

Advances in control theory are needed to deal with systems exhibiting complex nonlinear behavior, distributed parameter systems and, in particular, *delay systems*. These functional models are involved in the description or explanation of phenomena generated by transportation, transmission, propagation (of materials, energy or information) but also of the computation times that information processing needs. Taking these complexity sources into consideration can still be considered as a research area but, besides, it opens a wide new area of concrete and promising application, such as those described below.

In dealing with this kind of complex systems, a number of paradigms on which classical as well as modern control theory are based are going to lose some of their significance. Indeed, in a system with several thousand state variables, concepts such as those of equilibrium, stability of an equilibrium and asymptotic convergence to an equilibrium no longer can be understood in the classical sense of Lyapunov. Likewise, performance of a control system no longer can be understood in those simple yet powerful ways related to the notion of bandwidth, sensitivity function, complementary sensitivity function, induced-norms, etc. Notions such as reachability and observability may still keep a role as measures of interaction between internal and external variables, but their importance in control design may take a different connotation. New paradigms have to be developed, leading to mathematically rigorous analysis of performance based on formal models and consequent systematic design procedures.

2.2 *Anticipated new developments*

Control Design is more than the design of feedback algorithms. Most of the software that actually implements a controller deals with exceptions, sensor failures, supervision of signal ranges etc. and performs logic and switching functions. This leads to the open problem of the systematic design and verification of *hybrid dynamic systems*, consisting of continuous dynamics, sampled-data controllers and switching logic which is both scientifically very challenging and practically extremely important. The European Union e.g. funds a large project about hybrid control in the automotive industry. As rigorous verification or proofs of stability of real systems are hardly possible, simulation and testing is a very important area here. This requires simulation environments which can handle complex systems consisting of dynamic sub-models which are represented by different formalism.

Exiting new applications for controller design will come by the use of micromanipulators, e.g. to control the flow around the wing of an airplane, and in biological systems related to the rapidly growing understanding of the control mechanisms which control the development of and the production of proteins in living cells.

In computer science, the topic of "machine learning" has become very active in recent years. This has strong overlaps with adaptive filtering and control, but most of the researchers there are unaware of the large body of rigorous theory on adaptive filtering and control which has been developed by the control community. On the other hand, fresh ideas on algorithms and data structures have appeared which might be worth being looked at by control theoreticians as well. While purely data-driven adaptive control has almost nowhere been applied in practice despite the enormous amount of research devoted to this topic, the time might now be ripe for the development of really autonomous controllers.

2.3 *Likely new applications*

In *Communication Networks*, many users are sharing the same resource, that can be identified as a bandwidth. This may give rise to bit rate congestion: in such a case, waiting times increase and buffers overloads can corrupt the information. The offered quality of service (QoS) is directly depending on the control algorithms that can be designed and implemented. Such algorithms aim at regulating the flow at different nodes, so to maximize the bandwidth while avoiding congestion. Several different design techniques can be used to control access and congestion in a communication network: optimal control, game theory, nonlinear control, adaptive control. To keep together quality and quantity, adaptive schemes are useful, that achieve a dynamic control of the flow ratio allowed to the different applications. Such questions can be directly related to continuous control of time delay systems, the ratio (global flow)/(size of access unit) being sufficiently large, high flow rate networks can be considered as continuous time systems with delays (linear or nonlinear, depending on the complexity the design can deal with).

Embedded digital devices, that interact with the physical world via sensors and actuators which are widely distributed and linked via communication networks and whose actions are coordinated towards some specific control goal, are expected to proliferate in industrial applications. Examples of such *Networked Control Systems* have appeared in manufacturing plants, aircraft, automobiles, to name a few target applications. One of the main problems here is to adapt standard serial communication networks to exchange system information and control signals between various physical components of the systems that may be physically distributed. Of course, such networks induce time delays among the controller, sensors, and actuators. Specific strategies have to be defined to avoid network instabilities.

Virtual reality is developing at the impressive rate of 35 % per year. Its implementation requires three abilities: computer sciences for creating a virtual world (image processing, for instance), physiology and mechanics for modeling both the human perception (for instance, proprio-kinesthesics of touch) and its environment (rigid, elastic, soft), and lastly, engineering for designing and controlling behavioral man-machine interfaces (haptic interfaces). If one wishes to worthy approach the performance level of human perception (which is still not achieved today), such controllers have to handle complex systems with delays: on the one hand, kinematic models of moving and colliding objects are strongly nonlinear; on the other hand, computation algorithms for virtual reconstruction and imaging introduce irreducible time lags in the control loops.