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Theory, algorithms and technology in the design of control systems[☆]

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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. 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. Challenges for future theoretical work are modelling, analysis and design of systems in quite new applications fields. New effective real-time optimal algorithms are needed for 2D and 3D pattern recognition. Design of very large distributed systems has presented a new challenge to control theory including robust control. Control over the networks becomes an important application area. Virtual reality is developing in impressive rate arising new theoretical problems. Distributed hybrid control systems involving extremely large number of interacting control loops, coordinating large number of autonomous agents, handling very large model uncertainties will be in the center of future research. New achievements in bioinformatics will result in new applications. All these challenges need development of new theories, analysis and design methods.

Keywords: Control theory; Current key problems; Recent achievements; Trends; Forecasts

1. Introduction

Control deals with methods leading to an automatic decision process in order to improve the performance of a system (industrial, biological, economical, human, …). 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.

Control engineers are faced with the critical problem of reducing costs while maintaining or improving product quality,

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as well as systems safety and integrity. 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.

These needs provide several challenging problems for control theory and important aspects for controller design.

Controller design is based on information characterizing the process to be controlled. All information is of value and should not be discarded just because it does not conform to a particular model building procedure. 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, leading to so-called 'grey-box' models. Controller design methods should be prepared to use such models.

In recent years, the main advances in control theory have been concerned with a deeper understanding of the robustness issues and the development of new tools and models to cope with uncertainty. However, a generally accepted and versatile modelling framework for uncertainties is still missing. Moreover, new theory is 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 non-linear, hybrid and stochastic systems and to handle very large model uncertainties. There is also a need to develop "soft sensors", where several measurements are processed together. The interaction of the signals can be used for calculating new quantities which need not to be measured. Soft sensor methods may incorporate embedded software, signal processing, data fusion, etc. They can be utilized, e.g. for modelling, fault diagnosis, real-time control.

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.

Fig. 1 provides a graphical illustration of the evolution that has occurred in flight control. Application of more sophisticated, robust, intelligent, learning control solutions made possible to discover the air, to go out to the space and making the first steps on other planets.

This evolution will continue as future advancements are made in sensors, actuators, and controller synthesis methods which allow designing critical controller components in an optimal and robust fashion.

2. Current key problems

There are many diverse control design methods available today; each technique is particularly well suited for unique classes of problems and practical applications. Although a rich collection of powerful and successful synthesis methods are available, there are nevertheless still many challenging opportunities for further improvement. These are the key problems being addressed today by leading researchers in our field.

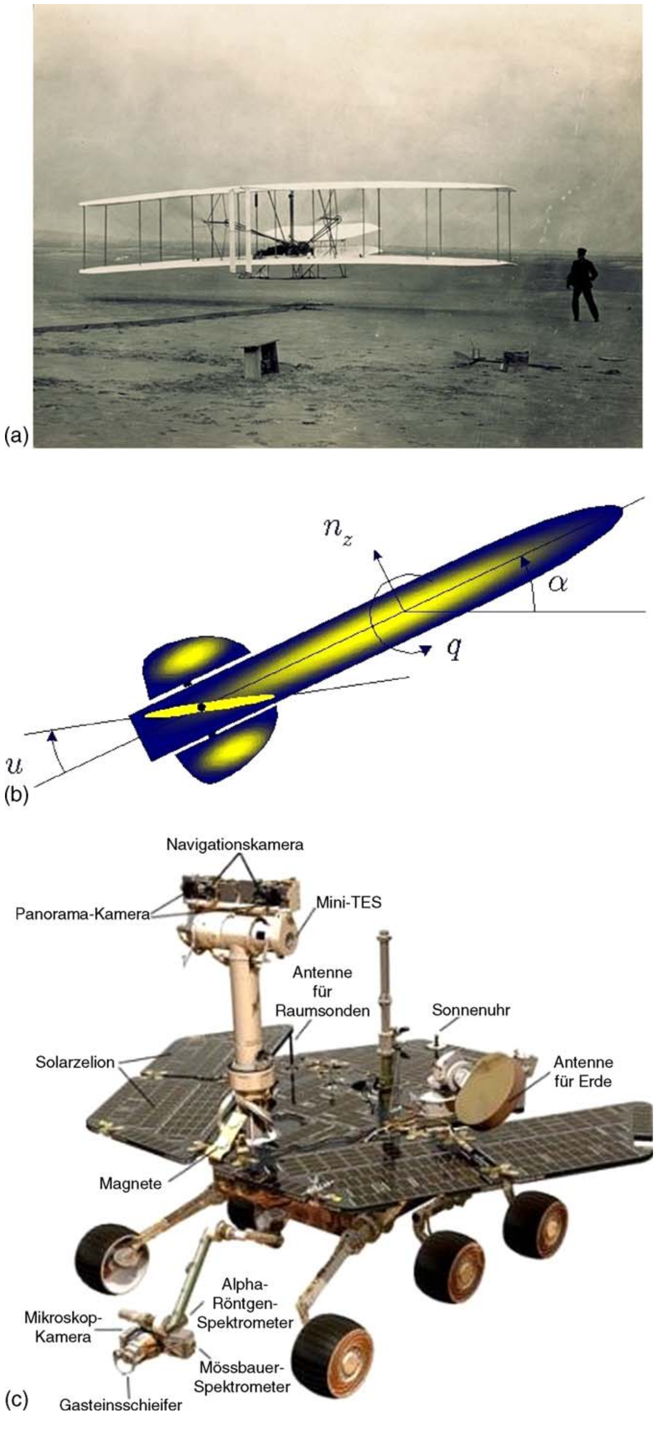

Fig. 1. (a) Past: origins of control. Wright-flyer, the first plane to master the three essential elements of flight: lift, propulsion and in-flight control; (b) present: rocket (LPV control of non-linear system). High-performance stability augmentation control, for example in missiles; (c) present and future: Spirit, NASA's latest Mars rover for a complex mission in uncertain environment.

This section discusses several of these opportunities (referring also to a previous overview by Isidori et al., 2002 and Camacho, Tempo, Yurkovich, & Fleming, 2005).

The vast majority of feedback control problems can be solved reasonably well by relatively simple *linear controllers*, namely *of* PI/PID-*type*. In industrial plants these controllers are still the most accepted. From an industrial perspective, efficient technique for the optimal design of restricted complexity controllers (such as PID or structured controllers) is still a challenging problem particularly in the case of complex systems (see also Quevedo & Escobet, 2000). Key problems are robust controller synthesis against structured uncertainties (requiring dedicated numerical solvers for non-convex bilinear matrix inequalities) or the computation of non-quadratic Lyapunov functions of bounded complexity for uncertain systems. Current concepts are suffering from their computational complexity, and insights into the exploitation of control structures for improving numerical algorithms are only starting to emerge.

Although linear controllers are widely used, there is also considerable interest in *control of non-linear systems with non-linear controllers*, considering the non-linear model of the plant. In many areas, there is a clear tendency towards high-performance controllers, e.g. in cars, airplanes, audio equipment, motors, steel-forming plants, etc. In these applications, there are complex rigorous and faithful models available for important processes either because they are used in the design of the system or because the commercial importance of high-quality control justifies this effort. Non-linear controllers, mostly based upon exact feedback linearization are not uncommon here. Another successful approach is to realize a controller by implementing the inverse model. But generally the model is not invertible. Designing sub-optimal non-linear inverse models is an interesting question. Also constraints and model uncertainties have to be considered. Stability analysis of non-linear control systems is a key issue. There are some available techniques, as, e.g. small gain theorem or robust stability analysis using SOS techniques for certain classes of non-linear systems.

Although of fundamental relevance, hardly any tool seems available that allows designers to computationally *analyze the trade-off between robustness and performance for non-linear systems of realistic size*. Techniques for determination of fundamental limits of performance for linear or non-linear uncertain systems are not suitably developed. Even in newly emerging areas such as congestion control over computer networks the trade-off between optimality and robustness plays a central role, with a strong emphasis put on the development of efficient computational tools.

In the optimal control area, *integrated optimal control problems of complex dynamical systems with delays*, *deterministic and stochastic disturbances*, *in the presence of uncertainties are of interest*. Degeneration of higher derivatives in some cases has to be considered. Detecting between convex and non-convex problems (problem reformulation, hidden convexity), measuring the gap between conservative convex relaxations and original non-convex problems is also a key issue. Optimal control methods are widely used not only in optimization of technological processes, but in investigating economical and other processes as well.

Reliable implementation of optimal and robust control algorithms, *pre-conditioning techniques especially for large-scale systems are of special interest*. In 2003 a panel discussion held on the 4th IFAC Symposium on Robust Control Design has addressed theoretical and practical issues of robust control (Bittanti & Colaneri, 2003). An entire recent issue of Control Systems Magazine (the amazing power of numerical awareness in control, February, 2004) is devoted to identifying key deficiencies, not only for existing software, but also for theoretical foundations for a reliable implementation of optimal controller synthesis algorithms or large-scale model reduction techniques.

The topic of *probabilistic robustness* also has gained significant attention. The presence of uncertainty in a system description has always been a critical issue in control. Moving on from earlier stochastic and robust control paradigms, the probabilistic methods provide a newer approach in the analysis and design of uncertain systems. Using the recently developed *randomized algorithms* guarantees a reduction in the computational complexity of classical robust control algorithms and in the conservativeness of methods like H_∞ control. The randomized algorithms are created using the principles of probability theory obtaining identically and independently distributed samples. Randomized algorithms can be applied efficiently, e.g. in congestion control of high speed communication networks. Randomized algorithms can be used for analysis of robust and optimal control of uncertain systems. Still, the numbers of required samples for theoretical guarantees is often prohibitively high, and many issues such as adaptive sampling strategies for reducing complexity remain to be explored.

Concerning *computational methods*, a large variety of specific problems in optimal and robust control can be translated into *linear semi-definite programs*. The constraints are formulated with respect to the cone of positive semi-definite matrices. These methods are shown to be globally convergent under suitable assumptions. Efficient algorithms for solving such problems have been available since the beginning of the nineties. It is of prime importance to understand how system theoretic structure (e.g. resulting from large interconnections of many low complexity systems) can be effectively exploited within *interior-point algorithms* in order to improve algorithmic efficiency and robustness for large-sized or ill-conditioned problems. Initial steps of developing dedicated algorithms have been taken for robustness analysis on the basis of integral quadratic constraints, but the extension to synthesis is largely open. One problem arising is numerical analysis (conditioning, stability, pseudo-spectra) for polynomials in systems control design (polynomial and behavioural approach). Another key requirement is the development of dedicated interior-point methods for convex (but potentially ill-conditioned or large-scale) linear matrix inequality (LMI) design problems (exploiting the structure, reducing the number of variables), and algorithms for control design via non-convex bilinear matrix inequality (BMI) optimization.

Model-predictive control can be viewed as a most successful practical technique. One reason of its success is in handling multivariable systems subject to input and output constraints. The industrial applications are supported by the fact that there are several large engineering companies specialized in providing software for predictive control solutions to all kinds of industries. Nevertheless there is still a number of challenging problems related to design of *predictive control algorithms for non-linear systems*, *large-scale systems*, *discrete event systems and hybrid type systems*. Guarantees of robust stability have to be given. For the non-linear case the focus is put mostly on the stabilizing control laws. The systematic inclusion of structured plant-model mismatch remains a challenging open problem. Computational issues providing systematic refinement schemes also have to be addressed. Due to the on-line optimization problem underlying all constrained predictive control problems, there is a natural match between this design strategy and the field of convex and non-convex optimization. Although in general the most successful predictive controllers are designed without involving Riccati equations, many of the modern research efforts investigate the stability problem by recognizing the similarities that the technique has with finite-horizon optimal control approaches. As a consequence, Riccati equations are a common trend of current analysis. Data handling is also an important question. Control algorithms incorporate the model of the process. It is important to use adequate system models built on the basis of physical knowledge and also using a priori knowledge. *Techniques that transform raw data into useful information and develop improved measurement methods including inferential estimation* (*called also* '*sensor-data fusion*' *or* '*soft-sensing*') *are of high interest*. Data based predictive control is an area of predictive control using the measurement data in a more effective way.

New developments in the technology of sensors and actuators will open the door to new control application fields such as medicine, biology, crystallography, optical communications and nanotechnology. *All these fields now need new efforts for modelling*, *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 communication are closely related areas in which complexity, reliability and safety requirements are integrated.

New effective real-time optimal algorithms are needed for 2D and 3D pattern recognition in the case of more complex sensing and signal processing used, e.g. for control of moving objects. Analytical and computational methods have to be used together.

New theories are needed in order to be able to handle highly complex systems such as *distributed hybrid control systems* (see also Antsaklis, Koutsoukos, & Z, 1998), systems involving an extremely large number of control loops, coordination of large numbers of autonomous agents, to control hybrid and stochastic systems and to handle very large model uncertainties. There is also a need to develop ''soft sensors'' as well as no-sensor-based control methods. Design of distributed hybrid systems has presented a new challenge to control theory. 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. The task is to describe and control interacting systems distributed in space.

Investigation of optimal control problems formalized in the framework of the theory of dynamic games requires further investigation (Petrosjan, 1995). The control design is seen as a game between two players: the controller algorithm, which is to be chosen by the designer, and the disturbances which represent the actions of, e.g. higher level controllers or unmodelled environmental disturbances. The two players compete over cost functions that represent properties that the closed-loop control system needs to satisfy (e.g. performance, robustness, reliability, safety). The control ''wins'' the game if it can keep the required property (e.g. performance, safety) for any allowable disturbance. The solution of the game theory problem provides the designer with controller algorithms as well as sets of safe states where the control ''wins'' the game. The sets of safe states can be used to construct an interface to switch among the controllers to guarantee the safe operation of the system. Such approach has been used, e.g. in control of automated highway systems.

Handling of saturation is of prime relevance for industrial practice. Recently suggested saturation allowance and avoidance techniques can be viewed as generalizations of classical anti-windup schemes. Saturation allowance techniques consist in allowing saturation non-linearities in the loop by counteracting their adverse effects, whereas saturation avoidance techniques consist in using set invariance conditions so as to avoid saturation non-linearities ensuring that the closed-loop system is always linear. Control structures ensuring similar saturation properties for the plant and system state variables could provide advantageous performance in case of saturation.

The extension of the internal model principle to non-linear systems has lead to the development of a theory of non-linear servomechanisms, and to systematic design of feedback laws for asymptotic tracking/rejection of fixed classes of exogenous inputs. Non-linear adaptive mechanisms can be incorporated in the design, so as to achieve autonomous tuning of the parameters of the internal model.

Practical aspects of control arise problems which have to be analyzed theoretically and handled practically, e.g. with MIMO processes the manipulated variables are sometimes correlated. They can be reduced to uncorrelated ones by *principal component analysis* (PCA). Controlled signals sometimes are not measurable (e.g. crystallisation state) or can be measured only with big dead time (e.g. chromatograph). Such signals can be estimated or predicted based on measurable signals (e.g. pressure, plate temperatures in a distillation column). *Qualitative models* describe the system dynamics by qualitative parameters and signals, e.g. by statement that the level of a tank is high, normal or low. Special control algorithms were developed for such processes.

Supervising methods are very important with complex control solutions. A control system can become unstable (because of changing of the system parameters or bad controller tuning), it can become oscillating (e.g. because of stick and slip of a valve), or not feasible (e.g. because of some hard limits). Supervising methods are required to monitor and detect such situations. These methods are known as control performance monitoring (CPM) or control loop condition monitoring (CLCM), but also fault detection is a familiar procedure. Adaptive control needs also permanent supervisory.

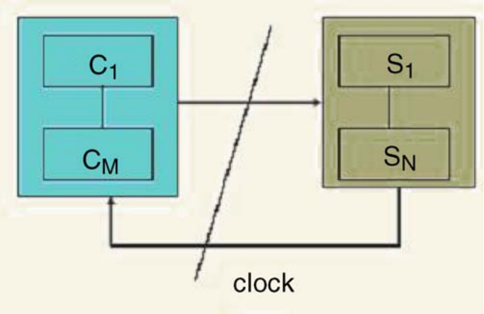

Fig. 2. Selection of the controller as a function of the environment.

In the presence of large modelling 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* (Fig. 2).

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. 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 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 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, 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. Switching control of linear and non-linear plants has had 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 of a wide variety of applicative problems where switching control comes about in a natural fashion. Besides being viewed in some applications as a constrained control problem, at least from a theoretical basis, the interest in hybrid/switching control strategies has also been spurred by the enhanced possibilities of stabilization and control performance that can be offered compared with more traditional control design methodologies. Switching control poses several interesting theoretical problems, due to the intrinsic non-linearity arising in the switching mechanism (between plants or controllers) even when dealing with simple linear systems. The relation between state-driven and time-driven switching strategies should be better explored as well as the optimization of performance criteria in terms of switching time-instants subject to dwell-time constraints.

Hybrid systems also arise, e.g. in modelling of a genetic network. Probably the simpler example bridging the disciplines in control design and system biology is the dynamic interaction of genes and proteins. Roughly speaking the dynamics can be modelled as a second order switching system that depends upon unknown concentration rates and activation thresholds to be estimated from data (micro-arrays of gene expressions). This turns out to be a very interesting data driven identification problem that can be addressed by means of suitable hybrid identification tools. Of course, complex models call for high complexity identification tools that possess a hierarchical structure and incorporate clustering techniques to combine genes that behave similarly. It is important to stress the fact that important biological questions can be translated into the proper language of systems and control, like reachability, stability of equilibria or limit cycles.

Periodic control is traditionally an important area in control design (Bittanti & Colaneri, 1999). One reason is that periodic control arises naturally when dealing with intrinsically periodic models or artificially, for instance in multirate-sampling (Fig. 3.) or when using periodic/repetitive controllers for time-invariant plants.

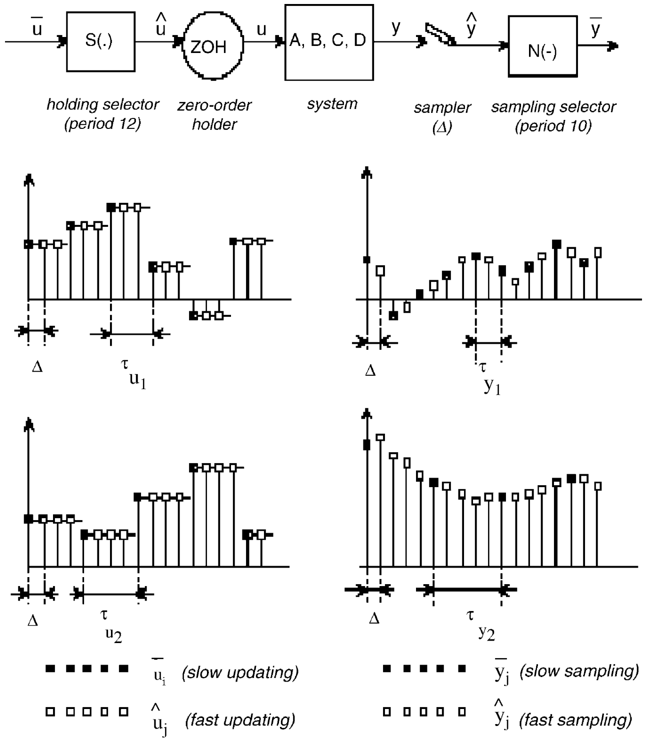

Fig. 3. Multirate system mechanism.

Fig. 4. Small satellite.

A typical example of the first type is given by the problem of vibration attenuation in helicopters. In the formulation of the associated individual blade control problem the dynamics of the rotor blade can be satisfactorily described in forward flight by a time-periodic model, with the period equal to the rotor revolution frequency. Another application of periodic models is in the attitude stabilization and control of satellites. The interaction between the geomagnetic field and the on-board magnetic field is periodically modulated with a period equal to the period of rotation of the satellite around the earth. Hence, the attitude model obtained by linearization of the satellite dynamics around the orbit is essentially periodic (Fig. 4).

Another reason that spurred the research activity on periodic systems is that periodic time-varying actions can outperform over steady state operations of some industrial processes. This observation germinated in the field of chemical engineering (cyclic operation of catalytic reactors), and is now a common paradigm in many application fields. A few problems in the area of periodic control merit a deeper insight. It is well-known that there are time-invariant linear systems which are not stabilizable by memoryless constant output feedback, but that can eventually be stabilized by periodically time-varying memoryless output feedback.

A complete corpus of results on this problem has not been provided yet so that it needs to be further studied. Also, frequency-domain techniques for periodic systems and their use in control and filtering are not commonly known. Analysis of these problems can bring new theoretical results and challenging industrial applications. The underlying theory is far for being trivial, since it stems from the algebraic properties of non-commutative polynomials.

There is a necessity to develop a new integrated design approach to solve the class of stochastic optimal control problems for which the certainty equivalence principle is not valid (Shinar & Turetsky, 2003). This difficulty arises in automatic control problems where either the dynamics or the measurements are non-linear, as well as in cases where the random disturbances are not Gaussian. Classical positional control problems with random bounded disturbances (e.g. in interceptor guidance) or dual adaptive control problems when parameter estimation and control is combined into an adaptive control strategy belong to this class. There is a renewed interest to solve these problems. Conceptually, the way to solve stochastic optimal control problems is by stochastic dynamic programming. This is, however, not a feasible practical approach. The ‘‘curse of dimensionality’’ known in deterministic dynamic programming becomes much worse in the general stochastic case, involving the numerical calculations of the conditional expectations. The development of a new integrated practical design approach for optimal solving the family of problems, where the certainty equivalence principle is not valid, requires a joint effort based on close cooperation of two scientific communities, namely the respective experts in estimation and in optimal control theories.

Robust control of large-scale systems raises important questions. 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 is an important question.

3. Recent major accomplishments and trends

As noted above, there are many challenging opportunities for further advancement of the diverse control design methodologies. The ‘‘good news’’ is that many significant accomplishments have been made within the last few years; this section describes some of those results. In addition, it is apparent that several trends are now developing within the design methods field, these are also discussed. The other ‘‘good news’’ is that several design methods that were considered to be ‘‘theoretical’’ just a few years ago are now finding practical applications within many industries.

Major recent accomplishments in the area of *predictive control* include significant results concerning robust stability 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.

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 optimization 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, non-linear system analysis and design.

In Markovian jump linear systems the concept of almost sure stability has been investigated. A necessary and sufficient condition has been worked out and reliable testable conditions have been proposed via *randomized algorithms* (Tempo, Calafiore, & Dabbene, 2005). The relation of *stochastic stability and deterministic stabilizing strategies of switching systems has been partially clarified*. LMI approach to switching stabilization problems has also been investigated. Many aspects wait for a better clarification, including the Lyapunov approach for control affine systems and the optimal switching sensor scheduling.

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. A fault detection scheme for periodic systems has been proposed via standard state-space techniques, but a preliminary investigation shows that a frequency-domain approach is possible and could solve the problem in a more elegant way.

While 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, *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. Gain-scheduling techniques on the basis of linear parameter-varying controller synthesis have been further developed. One of their applications is designing spatially distributed controllers for spatially distributed systems.

Key contributions have been made for the *analysis of state feedback and estimator synthesis of uncertain delay systems*, or for the H_∞ or H_2 design of output feedback controllers with a delay in the control channel. Moreover well-known upper bound optimization techniques for multi-objective controller design with H_∞ specifications could be successfully complemented with lower bound computations in order to estimate conservatism. In addition important classes of system interconnections (such as nested structures) have been shown to be amenable for *Youla-Kučera parametrization based optimal synthesis of structured controllers*.

As real systems are generally non-linear, describing non-linearities and handling non-linear 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 non-linear systems.

In the area of optimal control there are some new results concerning the *generalization of the Pontryagin's maximum principle* for control design related to problems with infinite-horizon. The necessary optimality principle is expressed in the non-linear system of Hamiltonian differential equations. Sufficient conditions of optimality are obtained for a class of dynamic systems using cocavity properties of the Hamiltonian function. The existence and uniqueness condition of a saddle-type equilibrium is obtained. The results are widely used in various applications, particularly in *models of economic growth*. A non-linear stabilizer for optimization of R&D investment policy providing proportional techno-economic growth has been constructed. The feedback principle for optimal R&D intensity is realized in terms of technology productivity, production level and costs. Based on the econometric data the identification procedure can be implemented for the basic model parameters such as the discount rate, factors of efficiency of the technology, cost effectiveness of R&D investments, estimation of delay time of investments, etc. With the constructed feedback technology with small additional investments and restructuring of the sources increasing returns, technology development and better consumption index could be reached.

New results have been provided related to the problem of *time-consistency of solutions in dynamic games*. In conflicting controlled dynamic systems modelled by differential games the optimal solutions are time inconsistent. The so-called ''imputation distribution procedure'' was introduced, which enables to regularize the problem and get the time-consistent solutions. As basic model the n-person *cooperative differential games* were considered. In n-person differential games as in classical simultaneous game theory different solution concepts are used. At the same time not much attention is given to the problem of time-consistency of the solution considered in each specific case. This may follow from the fact that in most cases the Nash equilibrium turns to be time-consistent, but not always. The time-consistency of solutions takes place in exceptional cases. The problem becomes more serious when cooperative differential games are considered. Usually in cooperative settings players agree to use such control strategies which maximize the sum of the player's payoffs. It is proposed to introduce a special rule of distribution of the player's gain under cooperative behaviour over time interval in such a way that time-consistency of the solution could be restored in a given sense.

3.1. Applications

With a delay of about 10 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 non-linear and robust control methods.

One particularly interesting application area is *control of smart structures*. 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 hysteresis effects can be incorporated into the controller design process.

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 aiding 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.

Predictive control has numerous industrial applications (Qin & Badgewell, 2003). 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 effort in the projects is spent to identify linear models of sufficient accuracy from plant experiments.

4. 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 non-linear control algorithms are to be developed and applied. Non-linear 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 numbers 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

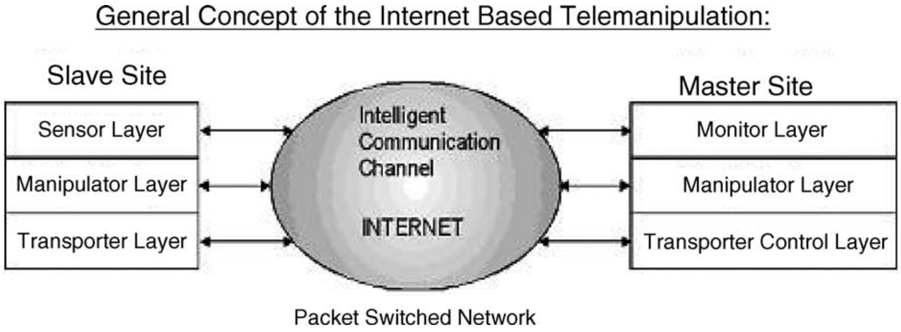

Fig. 5. Internet based telemanipulation and nanomanipulation.

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 type of applications.

Distributed hybrid control systems involving an 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 center of future research. Dynamic game approaches will also facilitate the analysis and control of such systems.

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.

Figs. 5 and 6 illustrate the Internet based telemanipulation and nanomanipulation. Main challenges are handling of varying time delays and bandwidth scaling in nanomanipulation converting the nano dimensions visible.

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 even in unknown or dangerous environment. Cognitive vision, description of behaviour based on cognitive knowledge gains significant emphasis.

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 multiagent distributed communication systems, mass production in the automotive industry, in consumer electronics, in microelectronics, control of

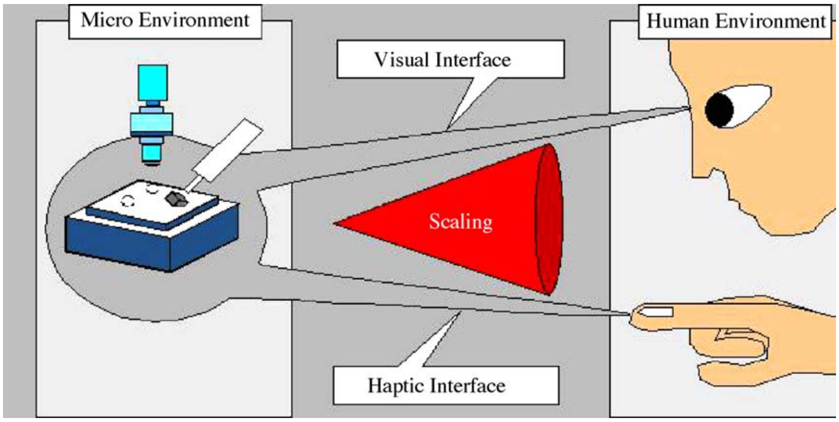

Fig. 6. Micro/nano teleoperation system.

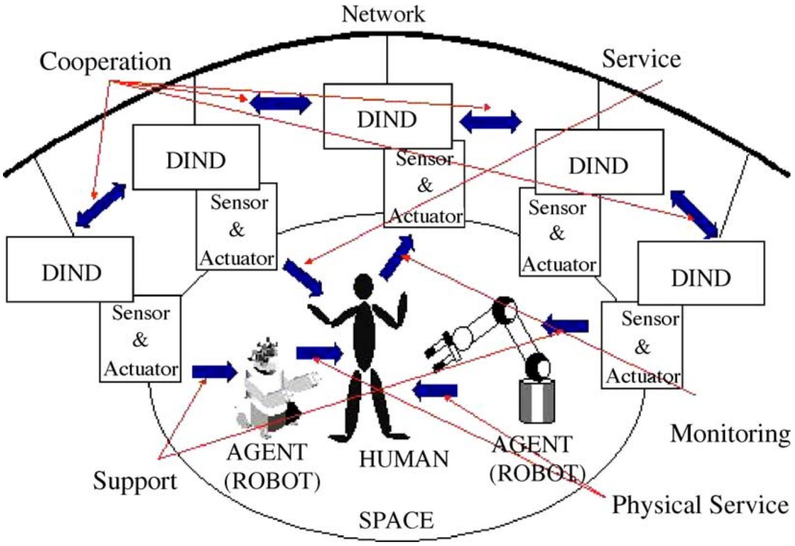

Fig. 7. Ubiquitous sensory intelligence concept.

environmental protection technologies, control of production of renewing energy resources, etc. (Korondi & Hashimoto, 2003).

Intelligent control of complex distributed systems with moving and cooperating objects could be realized with *intelligent space* with ubiquitous sensory intelligence is shown in Fig. 7.

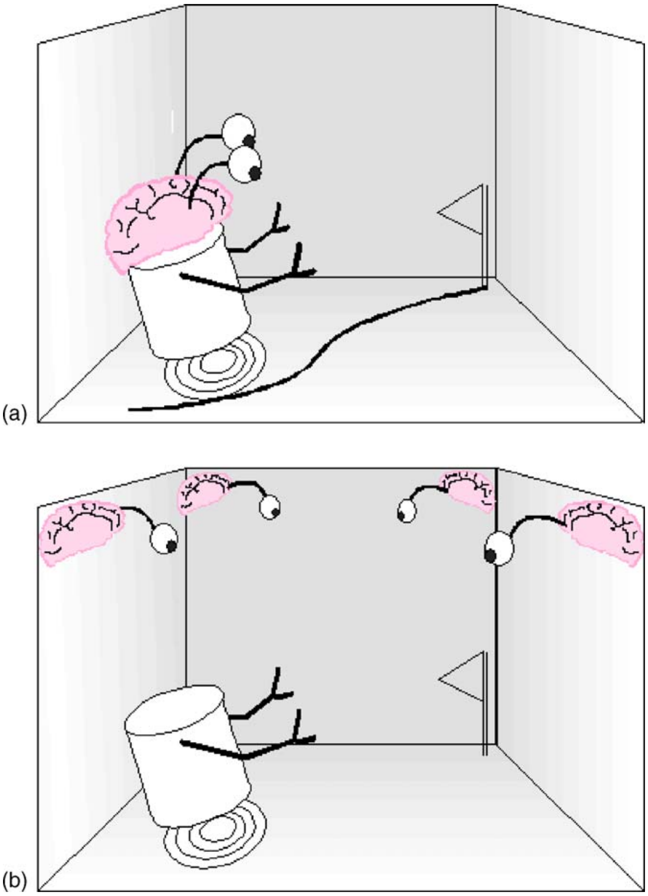

Fig. 8. Robotics based on own and on ubiquitous sensory intelligence.

The ubiquitous sensory intelligence is realized by distributed intelligent networked devices (DIND), robots, which are physical agents of the intelligent space, and human. In the intelligent space, DINDs monitor the space, and achieved data are shared through the network. Since robots in the intelligent space are equipped with wireless network devices, DINDs and robots organize a network. The intelligent space based on ubiquitous sensory intelligence supplies information to the Human beings, thus ensuring cooperation between robot agents and users. Conventionally, there is a trend to increase the intelligence of a robot (agent) operating in a limited area. The ubiquitous sensory intelligence concept is the opposite of this trend. The surrounding space has sensors and intelligence instead of the robot (agent).

A robot without any sensor or own intelligence can operate in an intelligent space. The difference of the conventional and intelligent space concept is shown in Fig. 8. An intelligent space, which can sense and track the path of moving objects in a limited area, can learn the usual events and can recognize the abnormal emergency situations.

References

Antsaklis, P. J., Koutsoukos, X. D., & Zaytoon, J. (1998). On hybrid control of complex systems: A survey. *European Journal of Automation, 32*(9–10), 1023–1045.

Bittanti, S., & Colaneri, P. (1999). In J. G. Webster (Ed.), *Periodic control. Encyclopaedia of electrical and electronics engineering*. John Wiley and Sons Inc.

Camacho, E. F., Tempo, R., Yurkovich, S., & Fleming, P. J. (Eds.). (2005). Fundamental issues in control. *European Journal of Control. Special Issue 11(4–5).*

Isidori, A. et al. (2002). IFAC 2002 milestone report on design methods. Plenary papers, survey papers and milestones (preprints). In *Proceedings of the IFAC world congress*.

Korondi, P., & Hashimoto, H. (2003). Intelligent space, as an integrated intelligent system. *Keynote paper of the Proceedings of the international conference on electrical drives and power electronics* (pp. 24–31).

Petrosjan, L. A. (1995). The shaply value for differential games. In G. Olsder (Ed.), *New trends in dynamic games and applications* (pp. 409–417). Birkhauser.

Qin, S. J., & Badgewell, T. A. (2003). A survey of industrial model predictive control technology. *Control Engineering Practice, 11*, 733–764.

Quevedo, J., & Escobet, T. (Eds.) (2000). *IFAC workshop on digital control—Past, present, and future of PID control*. IFAC Proceedings Volume. Terrassa, Spain: Elsevier, ISBN: 0-08-043624.

Shinar, J., & Turetsky, V. (2003). What happens when certainty equivalence is not valid?—Is there an optimal estimator for terminal guidance?. *Annual Reviews in Control, 27*(2), 119–254.

Tempo, R., Calafiore, G., & Dabbene, F. (2005). *Randomized algorithms for analysis and control of uncertain systems*. Springer-Verlag.

Bittanti, S., & Colaneri, P. (Eds.) (2003). *Witherto robust control? Panel discussion. 4th IFAC symposium on robust control design*. IFAC Proceedings Volume. Milano, Italy: Elsevier, ISBN: 0-08-00440126.

Control Systems Magazine (February, 2004). Special issue: The amazing power of numerical awareness in control.

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