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SOME RECENT ADVANCES OF AUTOMATIC CONTROL IN CHINA

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Abstract: This paper, preluding with a brief historical account, gives a survey of some main results in both theory and applications of automatic control, which have been accomplished by researchers living in the Chinese mainland over the past twenty years, particularly in recent years.

Keywords: Automatic control, systems, feedback, control theory, control applications.

1. INTRODUCTION

Advances of any branch of science and technology are inextricably linked to its social environment and historical background. Automatic control in China is not an exception.

China is one of the world's four major countries with ancient civilizations, having a civilized history of five thousand years. It is therefore not at all surprising that many automatic equipments which had been used to reduce or replace the manual or mental labour were invented in ancient times in China. Typical examples include the *water clock* for automatically counting the time (circa 1400 - 1000 B.C.); the *south-pointing-chariot* for automatically indicating the direction (A.D. 235); the *armillary sphere* for automatically simulating the motion of celestial bodies (A.D.78-139); the *seismograph* for automatically detecting the indications of an impending earthquake (A.D. 78 - 139); and the *waterpowered astronomical apparatus*(1086 - 1092) constructed by combining the armillary sphere, celestial globe and the water clocks, etc. (Wan, 1991; Liu, 1962; Needham, 1954).

While the West was a backwater in mediaeval times, China had reached the heyday of Tang and Song Dynasties (618 - 1279). The agriculture-centered pragmatic system of science and technology of China had led the world for about one thousand years (Needham, 1954). The well-known Chinese four great ancient inventions (papermaking, gunpowder, compass and printing) hastened the parturition of the modern science after being spread into the Europe during the 12th - 15th centuries. Unfortunately, the Chinese feudal system, after reaching its glorious top, had been on the wane since the mid 16th century until it was overthrown in 1911. The root-taking and development of the modern science in China had been further impeded by the tremendous social turbulences resulted from either internal disturbances or foreign aggressions over the past century.

The research on automatic control in the modern sense in China can be traced back at least to the publication of the book *Engineering Cybernetics* by Tsien (1954). In the preface, the author stated that "the justification of establishing cybernetics as an engineering science lies in the possibility that looking at things in broad outline and in an organized way often leads to fruitful new avenues of approach to old problems and gives new, unexpected vistas". Aiming at this, the author gave a comprehensive study of automatic regulation and control theory for various engineering systems from an engineering science standpoint. This book was first published in English in the U.S.(Tsien, 1954) and was then translated into Russian (1956), German (1957) and Chinese (1958). The revised edition was also published (Tsien and Song, 1980). After Dr.Tsien came back to China in 1955, he initiated and led the development of the country's space program. In 1957, he was elected as a council member of IFAC representing China. Under his suggestions, the first research laboratory on modern control theory headed by mathematician Z.Z.Guan and control scientist J.Song, was founded in the Chinese Academy of Sciences in 1962, which afterwards promoted the development of modern control theory and its applications in China, especially in space technology.

The research on automatic control in China had been quite active in the first half of the 60s. The independent study and proof of the pole-placement theorem for single input linear systems together with the construction and analysis of iterative solutions for the LQ problem (Huang et al, 1964); the derivation of the frequency domain criterion for absolute stability of delay systems (Li, 1963); the investigations of optimal control problems under various constraints (e.g., Song and Han, 1965; Zhang, 1963); as well as the study of distributed parameter control systems (Bi and Wang, 1966), are some examples. Unfortunately, this "prime time" did not last long, the whole country was soon drawn into the social turmoil triggered off by a political campaign called "*The Cultural Revolution*" (1966 - 1976). Many professors and experts were compelled to leave their posts.

With the termination of this campaign at the end of the 70s and the implementation of Deng Xiaoping's open door policy, China welcomed the resurrection of the spring of science. From 1979 on, the Chinese Control Conference (CCC) has been held annually, and the regular research on automatic control in China resumed gradually.

The story to be told below started at the early 80s. We will present a survey of some main results accomplished in the Chinese mainland in both theory and applications of automatic control in the following seven major areas: linear and singular systems, nonlinear systems, system identification, adaptive control, stochastic control and optimization, distributed parameter systems and discrete-event/manufacturing systems.

It goes without saying that this is quite a task. Given the multifarious developments and the overwhelming literature in automatic control, it is hard to do justice to even only one of the above-mentioned seven areas in a single article with limited spaces, let alone to all of them at once. Moreover, we have tried to be objective, but the colour of the authors' own experience and flavor may still be stronger than expected, and if that is the case, the indulgence of the readers particularly of those whose contributions were overlooked or undervalued is requested.

2. LINEAR AND SINGULAR SYSTEMS

2.1 *Output Feedback and decentralized Control*

Although linear system theory has already relatively matured since the end of the 70s, some problems still remain open and attract constant research attentions. One such problem is related to output feedback. By using certain properties of a matrix inequality, Huang and Li (1989) obtained a necessary and sufficient condition for optimality of linear-quadratic(LQ) control of continuous-time linear systems with output feedback. They also pointed out that such a problem is not well posed in general. The longstanding Morgan problem was investigated for a class of non-square linear systems by Xu (1996). By using the notion of "(A,B)-*characteristic subspace*", Zheng and Han(1986) gave a detailed study of various properties of decentralized systems, e.g., fixed mode, input-fixed-mode and output-fixed-mode, etc.

2.2 *Analysis and Control of Systems with Parameter Perturbations*

Since the mid-1980's, there have been extensive research efforts devoted to the analysis and control of systems with parameter perturbations. Several significant results including the *edge theorem* and the *diamond theorem* were obtained in the western literature, following the introduction of the now well-known *Kharitonov theorem* into the West. In order to put these theorems in a unified framework, Huang and Wang (1991) established the following general *boundary theorem*: Under affine parameterizations, the D-stability of any family of polynomials with degree ≥ 2 can be determined by that of its relative boundaries. From this result, all the above-mentioned theorems can be deduced conveniently. Later, Yu and Huang (1993) generalized this boundary theorem to the case of complex polynomials, Wang(1993) found an equivalent form for reducing the complexity of the stability test, and Wang and Huang(1993) gave a boundary theorem for general distributions of roots. The problem whether or not the stability of a family of convex combinations of polynomials can be determined by only checking that of the ends of this family was studied for both continuous- and discrete-time systems, and simple and weak sufficient conditions in terms of the rate of the arguments were given (Huang et al., 1993; Wang and Huang, 1992).

Besides, the two-vertexes test for strong stabilizability of interval systems (Wang, 1997), the strictly positive real test (Wang and Huang, 1996) and strictly positive real stabilization (Jia et al., 1992, 1994) were also investigated. For optimization of LQ regulator systems, insensitivity of optimality to parameter perturbations was considered by Zheng(1986).

All the above results enriched the robust analysis and control theory of systems with parameter uncertainties. Other robust control design methods were discussed in (Zhong, 1996; Wu and Xie, 1997).

2.3 *Singular Systems*

Consider the following singular linear system:

$$\begin{cases} E\dot{x} = Ax + Bu \\ y = Cx \end{cases}$$

where E is a singular square matrix. This kind of systems comes from several sources including economics, power systems and missile systems.

The theoretical investigation of this kind of systems was undertaken in China at the beginning of the 80s. Interesting progress has been made in various aspects including the design of normal state observers (Wang and Dai, 1986). In particular, the internal model principle of singular systems was obtained by using regular dynamic compensators, and the notion of *normalization of singular systems* was introduced and used in the system design (Dai and Wang, 1987). The research interest in singular systems was shifted to optimal filtering and control at the end of the 80s (Wang and Wang,1988b; Wang, 1989). The local maximum principle was derived (Wang, 1992) and structural properties of singular decentralized control systems were discussed (Wang and Wang, 1988a).

3. NONLINEAR SYSTEMS

3.1 *Affine Nonlinear Systems*

Differential geometry, Lie group and Lie algebra are now well-known to provide suitable frameworks for structural analysis and feedback control of nonlinear systems. By using these powerful tools, various state feedback linearization problems have been studied for the following affine nonlinear systems:

$$\begin{cases} \dot{x} = f(x) + g(x)u, \\ y = h(x) \end{cases}$$

Some necessary and sufficient conditions for global linearization and linearization of systems with outputs were obtained (Cheng et al.,1985, 1988). The set of linearizable systems was shown to be of measure zero in Whitney topology (Cheng et al., 1991). Some reasonable conditions were given for the equivalence of controlled-invariant distributions for both singular distribution case(Cheng and Tarn, 1989) and global case (Dayawansa and Cheng et al., 1988). Necessary and sufficient conditions as well as a design method were presented for input-output non-interacting decomposition (Cheng, 1988). The observability of nonlinear systems over Lie groups with output on cosets has been considered, and the necessary and sufficient condition for the systems to be observable has been obtained (Cheng et al., 1990).

A number of other interesting results on nonlinear systems have also been published by using diverse methods. The nonlinear observability was studied by using differential linear vector spaces, and the reverses for linear and nonlinear control systems were treated via a unified approach (Zheng and Cao, 1993). By parameterizing the set of feedbacks, a design method for noninteracting stable control was presented (Xia, 1993). For a class of homogenous systems, the H_∞ control was designed via a particular form of stabilizing controls (Hong and Li, 1997). Feedback linearization problems were considered for multi-input affine nonlinear singularly perturbed control systems (Huang and Xu, 1993). A simple and easy-to-use controller called *"auto-disturbance-resistance controller"* was developed by making use of certain nonlinear properties (Han, 1998). Finally, inverse system methods for feedback linearizations were also investigated (Li and Feng, 1991).

3.2 *Systems with Similar and Symmetric Structures*

The investigations of general nonlinear systems are hard and complicated. Fortunately, for systems that came into being during the evolution of the nature, e.g., biological and social systems, their structure are formed in a "self-optimizing" way in the process of adapting to the changes of the environments. Symmetry and similarity are two notable characteristics of such systems. It is conceivable that the suitable use of these characteristics can lead to simplifications of many problems in many aspects (Zhang, 1994).

Motivated by the above perspective, the nonlinear control group at Northeast University has conducted a series of research over the past ten years. It has been demonstrated that symmetric and similar structures can lead to the decomposition of the original systems into lower dimensional subsystems, which can then lead to the design of simplified control laws for many problems of the original ones (Zhao and Zhang, 1991), e.g., the linearization problems and the control of composite large scale systems (e.g.,Yang and Zhang, 1996; Qian et al., 1998). Besides, some new notions such as "symmetric circulart structure" and " quotient similarity" etc. were introduced and investigated (c.f., Zhao and Zhang, 1991; Hu et al.,1997).

3.3 *Variable Structure Control*

A design method called *"reaching law approach"* was developed in (Gao, 1990; Gao and Huang, 1993), which may be used to overcome the obstacles in extending the variable structure control theory from scalar variable systems to multivariable ones. This approach makes the controller design easy and flexible, while ensuring good dynamic properties of the control systems(Gao et al., 1995).

3.4 *Nonlinear Control of Power Systems*

Based on the differential geometry approach of nonlinear systems, a new design method for the excitation control of generators in multimachine power systems was developed (Lu and Sun, 1989; Sun et al.,1993, 1996). Up to now, it has been applied to more than ten large-scale power systems in China, with electric generating capacity ranging from 50MW to 300MW. Both simulation /experimental study and on-the-spot measurements demonstrated that after adopting this kind of control laws, the safety, stability and dynamic performances of the power systems can be improved significantly.

4. SYSTEM IDENTIFICATION

4.1 *Time-Invariant Stationary Systems*

In the mid-1980's, the problem of estimating the transfer function of a linear stochastic system was investigated. The transfer function is parameterized as a black box with no order given *a priori*. Under certain regularity conditions, it was shown that the variance of the transfer function estimate at a certain frequency is asymptotically given by the noise- to-signal ratio at that frequency, multiplied by the ratio of the model order to the number of data (Ljung and Yuan, 1985). An analytic solution to the optimal input design in open loop identification was given by Yuan and Ljung (1985). These results can be extended to multivariable systems (Yuan and Ljung, 1984).

In order to eliminate the bias of the standard least-square (LS) method caused by the presence of the colored noise, Feng et al.(1986) introduced a new approach called *"bias-eliminated least-squares (BELS)"*. This approach can be applied to a variety of situations including time lag systems (Zheng and Feng, 1990), open or closed loop systems and set-membership identification, etc. (Feng and Zheng,1991; Feng and Zhang, 1995; Zhang and Feng, 1998).

Model validation is important in practice to test if a given mathematical model can be falsified by the system data before it was put into use. In a recent work (Ljung and Guo, 1997), it was shown that the classical model validation procedures can in fact be used in robust identification for assessing the size of the unmodeled dynamics. To be precise, let $\widehat{G}$ be any given mathematical model, then the frequency weighted L_2 error between this model and the true system G

$$\int |\widehat{G} - G|^2 |U_N|^2 |L|^2 dw$$

can be bounded by three terms relating to the model validation function, the noise magnitude and the impulse response tail, respectively. For details see (Ljung and Guo, 1997).

4.2 *Time-Invariant Nonstationary Systems*

If the data that we obtained are essentially nonstationary, then the traditional notions like "spectrum" and "correlation function" that have been very useful in the stationary case will not make sense. In this case, the martingale theory on inequalities and convergences are known to be indispensable to the study of recursive estimation.

In the early 80's, Chen(1985) introduced a method called "the combined method of martingales and ordinary differential equations" in the consistency study of parameter estimation algorithms of nonstationary ARMAX models. This method has provided the first rigorous consistency proof of the stochastic-gradient-like algorithms under the traditional persistence of excitation (PE) condition, which was verified for an adaptive tracking control system (Chen, 1984). Later, more direct methods were introduced leading to a comprehensive convergence theory of various estimation algorithms (Chen and Guo, 1991), where the PE condition required on the data was considerably weakened, which made it possible to simultaneously get the optimality of both estimation and control in adaptive systems (Chen and Guo, 1987a).

The first paper that treats the strong consistency of recursive order estimation of nonstationary systems with feedback seems to have be (Chen and Guo, 1987b). Similar methods can also be used for delay estimation (Chen and Zhang, 1990). The estimation theory of infinite dimensional nonstationary linear systems hinges on asymptotic analyses of double array martingales (Guo et al., 1990). The most general result so far on "black-box" identification of nonstationary linear control systems seems to be that in (Huang and Guo, 1990), where both the coefficients and the orders of the systems are consistently estimated, without resorting to any *a priori* knowledge about the system orders, and without imposing the stringent positive real condition and the PE condition.

4.3 *Time-Varying Systems*

Since the beginning of the 90s, substantial progress has been made on the theoretical foundation of time-varying system estimation.

Consider the following basic time-varying linear regression

$$y_t = \theta_t^\tau \phi_t + v_t,$$

where $\{\theta_t\}$ is an unknown time-varying parameter vector process , $\phi_t \in I\!R^n$ is the stochastic regression vector (may be a nonlinear function of the observed input and output data), and v_t is the noise.

The estimation (or tracking) algorithms for the time-varying parameter process have the following general form:

$$\widehat{\theta}_{t+1} = \widehat{\theta}_t + \mu L_t (y_t - \phi_t^\tau \widehat{\theta}_t)$$

where $\mu \in (0,1)$ is the step-size (or $1-\mu$ is the forgetting factor). By suitably choosing the gain matrix L_t one can obtain the following three well-known and basic algorithms : the least mean square (LMS), the recursive least-squares (RLS) with forgetting factor, and the Kalman-filter (KF)-based algorithms.

The problems that need to be solved in theory are as follows : For a general and realistic correlated nonstationary signal process $\{\phi_t\}$,

(i) Do the basic tracking algorithms possess L_p- or exponential stability ?

(ii) How to analyze and calculate the tracking performances ?

(iii) How to choose the stepsize(forgetting factor) to minimize the tracking errors ?

For the first problem, the concept "*conditional excitation*" appears to be fundamental. The L_p-stability of KF was first established by using this concept in (Guo, 1990a). It was then used in (Guo, 1994) to establish a unified L_p-stability theory for all the LMS, RLS and KF algorithms. The exponential stability was later established in (Guo and Ljung, 1995a; Guo et al., 1997). On the basis of these stability results, the second and third problems above were investigated in (Guo and Ljung, 1995b; Guo et al., 1993, 1997). The main conclusions can be stated roughly as follows: The tracking error can be well approximated by a quantity that can be calculated via a deterministic recursive Lyapunov equation, while the "optimal" design of the step-size is a trade-off between tracking ability and noise sensitivity. In the special stationary case, the following simplified formula can be derived (Guo and Ljung, 1995b):

$$E[\tilde{\theta}_{t+1}\tilde{\theta}_{t+1}^T] \approx \mu R_v + \frac{\gamma^2}{\mu} Q_w, \quad 0 < \mu \ll 1.$$

where $\tilde{\theta}_t = \theta_t - \widehat{\theta}_t$, and R_v and R_w are quantities that depend on, in addition to the "energy" of the signals, the variances of the noise and the variation of the parameters respectively. Moreover, γ is a positive number reflecting the speed of parameter changes.

The above results provide a general rigorous mathematical theory for the estimation of time-varying parameters. It is worth noting that the LMS, RLS and KF algorithms are also basic ones in signal processing, and that tracking algorithms which differ from them can also be dealt with in the same framework(cf., Guo and Ljung, 1995b).

4.4 *Application Examples of Identification and Fault Detection*

On-line optimization of industrial processes is one of the areas where the techniques for time-varying parameter estimation play an important role. As an example, by using the RLS algorithm with stepsize chosen as $\mu = 0.005$, Sun et al.(1998) designed an on-line optimization package (ANOPT) and successfully implemented it in an acrylonitrile plant with an output of 50,000 tons per year in Northeast China in 1994. The acrylonitrile output was increased, the workers' labour intensity was reduced, and significant economic benefit has been gained since then.

Fault detection is an area closely related to system identification. Ge and Fang (1988) proposed an observer design method for fault detection based on robustness principles, and Zhou et al.(1993a) proposed a strong tracking filter (STF) based on orthognality principles. The STF has been applied to some practical problems including fault-tolerant control of the sensors of chemical reactors(Zhou and Frank, 1998) and fault-detection of the sensors of paper machines(Zhou et al., 1993b).

5. ADAPTIVE SYSTEMS

In recent years, much progress in both theoretical research and practical applications of adaptive control has been made in China. Adaptive control is a powerful method for dealing with systems with structure uncertainties. However, how much uncertainty can be actually dealt with by this method ? We proceed to answer this question by considering linear systems first.

5.1 *Adaptive Control of Linear Systems*

If the noise effect is not taken into account, then by suitably choosing the input signal, all the unknown parameters of the linear system may be determined within finite steps. Hence, to have a more justifiable theory, we consider the following discrete-time linear systems with random noises :

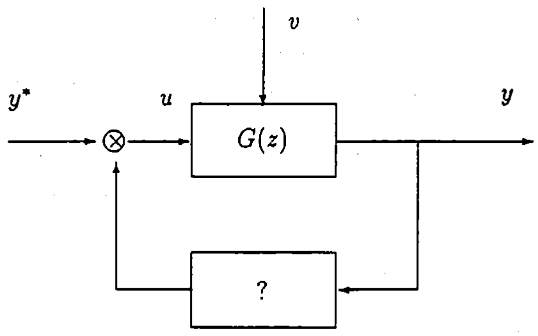

Fig. 1. Stochastic control systems with unknown linear TF.

where $G(z)$ is the transfer function (TF) with unknown coefficients. The discussion to be given below is divided into two cases.

- *Minimum-phase systems.*

The self-tuning regulator (STR) and model reference adaptive control (MRAC) are two typical design methods. However, since the later is essentially a specialization of the former, we are only concerned with STR here. Since the standard least-squares (LS) estimate has certain optimality with fast convergence rate in the presence of noise, it is natural and intuitively appealing to use the on-line LS estimates in updating the (unknown) parameters of the controller. Although this self-tuning idea can be traced back to Kalman about 40 years ago, it was not until the publication of the well-known paper "*On Self-tuning Regulators*" by Åström and Wittenmark in 1973 that intensive research activity was inspired in adaptive control on STR. Because the closed-loop adaptive system associated with the LS-based STR is a very complicated nonlinear stochastic dynamical one, the rigorous proof of stability and convergence of LS-based STR had been a longstanding open problem. It was finally solved in (Guo and Chen, 1991). Further study showed that the LS-based STR satisfies an elegant logarithm law and possesses the best possible rate of convergence (Guo, 1995)

- *Nonminimum-phase systems.*

Adaptive pole-placement(PP) and adaptive linear-quadratic-Gaussain (LQG) control are two basic design problems for this type of systems. A long-standing stumbling block in the theoretical study has been the following problem: how to guarantee the uniform controllability of the on-line estimated models ? Recently, this problem together with the adaptive PP and LQG control problems was resolved by a simple random approach in (Guo, 1996). The key ingredients of this approach are (i) a class of weighted LS algorithms having the celebrated self-convergence property, and (ii) a random regularization method having certain capability of optimization. This approach has recently been found useful also for adaptive control of bilinear and affine nonlinear systems(Xie and Guo, 1998). Other approaches involving the use of stochastic approximation methods for pole-placement problems are found in (Chen and Cao, 1997).

5.2 *Robustness, Nonlinear and Time-Varying Systems*

For ARMAX models with unmodeled dynamics , a robust stochastic adaptive controller was designed by using the LS method and a certain excitation method (Chen and Guo, 1988). Both the results and methods in the linear case can be applied to a class of nonlinear regressions and to some affine nonlinear models, save that the growth rate of the nonlinearities should be restricted in the discrete-time case (Xie and Guo, 1998). For minimum-phase linear time-varying stochastic systems, an adaptive control law can be designed to cope with slowly time-varying parameters in a stochastic averaging sense, bounded or unbounded disturbances and small unmodeled dynamics (Guo, 1990b). For nonminimum-phase systems, a typical case is the hybrid system with unknown parameters modeled as a finite state Markovian chain (Caines and Chen, 1985; Caines and Zhang, 1995). In the discrete-time case, an adaptive LQ control was designed such that the closed loop system is globally stable, whenever the transition speed of the Markov chain is suitably small (Huang and Guo, 1998).

5.3 *Understanding the Limitations and Capabilities of Adaptive Feedback*

To establish a general theory of adaptive control, it is necessary to understand the limitations and capabilities of adaptive feedback in the presence of uncertainties. Since to give a rigorous mathematical definition of adaptive feedback that differs from the ordinary feedback seems to be impossible (and probably not necessary also), the results to be presented below are actually applicable to any feedback (including the future "intelligent" feedback). Let u_t and y_t be the system input and output respectively, and let the information σ-algebra generated by $\{y_t\}$ be denoted by $\mathcal{F}_t \triangleq \sigma\{y_i, i \leq t\}$. Then u_t is an adaptive feedback $\Longleftrightarrow$ $u_t \in \mathcal{F}_t, \forall t$.

- *Uncertain nonlinear systems.*

Consider the following first order nonlinear system:

$$y_{t+1} = \theta f(y_t) + u_t + v_{t+1}, \quad \theta \in \mathbb{R}^1$$

where $\{v_t\}$ and θ are nondegenerate Gaussian noise process and unknown parameter respectively. Assume that there exists $b \geq 0$ such that the growth rate of $f(\cdot)$ satisfies,

$$f(x) = O(x^b), \quad x \to \infty.$$

It was found and proved in (Guo, 1997) that the above system is stabilizable by adaptive feedback $\Longleftrightarrow$ $b < 4$. This result describes the capabilities and limitations of adaptive feedback for controlling uncertain nonlinear systems. As elaborated on in (Guo, 1997), it also reveals the fundamental differences between adaptive control of continuous- and discrete- time systems as well as between deterministic and stochastic systems.

Furthermore, let $\theta \in \mathbb{R}^n$ be a vector unknown parameter with dimension n. If the admissible upper bound of b for the system to be stabilizable is denoted by $b(n)$ and is regarded as a measure of the capability of adaptive feedback, then $b(1) = 4$, and there are typical situations in which $b(n) \underset{n\to\infty}{\longrightarrow} 1$ (Xie and Guo, 1999). This demonstrates that the linear growth condition on the nonlinearities cannot be essentially weakened in general, unless the number of unknown parameters is limited.

- *Uncertain time-varying systems.*

Consider the following first order time-varying (nonlinear) system:

$$y_{t+1} = a(\theta_t)f(y_t) + u_t + v_{t+1}$$

where $\{\theta_t\}$ is a time-homogeneous Markov chain taking only two values in $\{1,2\}$, which can not be observed directly and is independent of the noise $\{v_t\}$. The diagram for the state transition of $\{\theta_t\}$ is as follows:

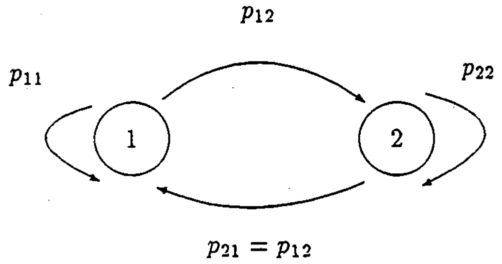

Fig. 2. State transition of the Markov chain

It was shown in (Guo and Huang, 1998) that this system is stabilizable by adaptive feedback $\Longleftrightarrow$

$$b \triangleq 1 - L^2[a(1) - a(2)]^2 U(H) > 0$$

where $L \triangleq \lim_{x \longrightarrow \infty} \frac{|f(x)|}{x}$, $U(\cdot)$ is a strictly monotonic function taking values in $[0, 1/4]$, H is the Shannon entropy (a measure of uncertainty) of the Markov chain $\{\theta_t\}$:

$$H = -\sum_{i=1}^{2} p_{1i} \log p_{1i}$$

If b is regarded as the capability of adaptive feedback, then it is obviously inversely proportional to the uncertainty H, and in the time-varying case, the system is never stabilizable as long as the growth rate of the nonlinearities is faster than linear (i.e. $L = \infty$).

For a long time past, the speed of parameter variations has played a key role in establishing stability of adaptive control of time-varying systems. However, upon noticing that the entropy H is a function of the transition speed p_{12} and when p_{12} varies from 0 to 1, its picture is symmetric about $P_{12} = \frac{1}{2}$, the following fact is evident: The capability of adaptive feedback is fully determined by the inherent uncertainty (H) of the system rather than the speed of parameter variations. This fact can be extended to general cases (Guo and Huang, 1998).

5.4 *Applications of Adaptive Control*

There are many practical applications of adaptive control techniques in China. According to the statistics made by Wu et al.(1991), at least 34 practical projects had been reported in the literature during the 80s, where adaptive control techniques were effectively applied. These applications involve in many areas including petrochemicals, metallurgy, pulp and paper, electrical power and machinery, space technology and biomedical engineering, etc. Further progress has been made in adaptive control applications in the 90s. Here we only present some examples:

(a) The "all-coefficients adaptive control method" introduced by Wu (1990) has been effectively applied to more than 200 control systems in at least five different kinds of plants.

(b) After establishing the stability of an adaptive controller for bilinear systems(Sun et al.,1993), Jin et al.(1996) applied it to the control of the pH value in a glutamic and crystallization with clear control effects.

(c) The "model-free controller" proposed by Han (1995) based on adaptive principles has been applied to a number of oil refineries and a paper mill. In particular, for the output temperature control of a 300,000 tons coke-oven in an oil refinery in Northwest China — a control problem with large delay and strong coupling, the quality of the product has been improved significantly after adopting Han's controller (Han, 1998).

(d) A weighted generalized predictive self-tuning controller was designed and applied to two 20 tons industrial boilers in a pharmaceutical factory in Tianjin by Chen et al.(1993). The combustion systems that had not been satisfactorily controlled previously by traditional methods have been well controlled since 1992.

(e) In view of the existence of large and time varying delays, parameter variations and extraordinary disturbances in power plants, a model reference adaptive predictive controller with a second order compensator was developed by Yang and Shen (1990). The first real application was carried out in 1992, and since then analogous controllers have been successfully applied in a number of power plants in China in the control of different processes such as main steam temperature, reheating steam temperature, main steam pressure and load following in different types of Boiler-Turbine-Generator (BTG) units. The control systems implemented by computers have ensured the desired and long run operating performances (Yang and Luo, 1995).

(f) A multivariable adaptive decoupling control was designed and successfully applied to coal pulverizing systems with ball-tube mill and storage bunker in a power plant (Chai et al., 1999). Such systems are characterized by strong coupling, nonlinearity, large time delay and uncertain disturbances. The control systems have been running safely and efficiently for nearly two years.

6. STOCHASTIC CONTROL AND OPTIMIZATION

6.1 *Stochastic Optimal Control*

Consider the following general stochastic control system with the diffusion coefficient containing the control term:

$$\begin{cases} dx_t = g(x_t, u_t)dt + \sigma(x_t, u_t)dw_t, & t \in [0,T] \\ x_0 \in I\!R^n \end{cases}$$

where $\{w_t\}$ is a standard Wiener process, and the domain of control is nonconvex. By introducing a second order variational equation together with its corresponding adjoint equation, Peng(1990) derived the stochastic maximum principle. Extensions to cases with random jumps and partial observations were considered by Tang and Li (1994) and Li and Tang (1995). The relationships between the maximum principle and the dynamic programming as well as the stochastic verification theorems within the framework of viscosity solutions were also investigated (Zhou, 1991; Zhou et al.,1997).

6.2 *Forward-Backward Stochastic Differential Equations*

The adjoint equation in the stochastic maximum principle is in fact a linear backward stochastic differential equation (SDE), with the terminal condition being a random variable measurable to the largest information sub-σ-algebra $\mathcal{F}_T$. Under certain conditions, Pardoux and Peng(1990) showed that the following nonlinear backward SDE

$$\begin{cases} dx_t = f_t(x_t, y_t)dt + [g_t(x_t) + y_t]dw_t, & t \in [0,T] \\ x_T \in \mathcal{F}_T \end{cases}$$

has a pair of unique adapted solution (x_t, y_t). A series of subsequent investigations on backward SDEs and forward-backward SDEs have been conducted (e.g., Ma and Yong, 1995; Yong, 1997), stimulated by their potential applications in finance.

6.3 *Stochastic Approximation and Optimization*

The objective of stochastic approximation(SA) is to seek the zeros or extremals of an unknown regression function by using the measurements in the presence of noises. Chen and Zhu(1986) introduced a randomly varying truncation to the standard Robbins-Monro algorithm, and weakened or removed some stringent conditions used previously in the convergence analysis. A comprehensive theoretical treatment of this truncated SA algorithm together with its applications in other fields was presented in the book by Chen and Zhu(1996). Global optimization problems based on simulated annealing were considered by Fang et al.(1997). Parallel processing and successive approximation techniques for optimization (Wu, 1989, 1990) and steady-state hierarchical optimization techniques (Wan and Huang, 1998) were also studied.

6.4 *Process Control and Optimization*

(a) By making use of both first-principles-model based real-time optimization techniques for reaction severity and multivariable coordinated predictive controls with nonlinear weighting for reaction severity, reactor temperature, preheat temperature and differential pressure of slide valve, Yuan et al.(1994) realized simultaneously the real-time optimization and advanced control of a fluid catalytic cracking unit in a petro-chemical corp., with optimum search period being 10 minutes. Since this control system was put into operation in 1996, it has been working well and significant benefit has been gained.

(b) By combining mechanism analyses with system identification, Sun (1993) studied the modeling of both individual apparatus and the whole production line of a pulp and paper process. In view of the existence of uncertainties, nonlinearities, couplings and large delays, Sun (1993) implemented optimization techniques and advanced control algorithms including multivariable robust predictive controls in this process. Significant economic benefit was reported.

(c) By adopting a multilayer feed-forward artificial neural network model, and combining region-optimization-based expert systems with process fault diagnoses, Zhou et al.(1996) successfully realized closed-loop on-line optimizations in a urea plant.

(d) In view of the fact that ordinary middle-sized blast furnaces(BFs) in iron and steel industries are poorly equipped with automation technologies, and that their detection facilities and stability of the quality of raw fuels are incomparable with those of large-sized BFs, a computer system for optimizing the operations of iron-smelting BFs was developed based on a synthesized modeling approach, which has been implemented successfully in the BFs of some iron and steel companies with significant benefit reported(cf. Liu et al., 1998).

7. DISTRIBUTED PARAMETER SYSTEMS

Distributed parameter systems usually mean dynamical systems that can be described by partial differential equations (DEs), functional DEs, integral equations, integral-DEs and DEs in abstract Banach spaces, their common characteristics lie in the fact that they all have infinite-dimensional state spaces. This kind of systems arise in many applied areas such as space technology, chemicals and energy resources, etc.

7.1 *Optimal Control*

For semilinear evolution equations defined on an infinite dimensional Banach space X :

$$\begin{cases} \dot{x} = Ax + f(t, x, u), & u \in U \\ x(t_0) = x_0, & x(t_1) \in Q \subset X \end{cases}$$

with the cost to be minimized being an integral index, Li and Yao (1985) proved that the maximum principle holds as long as the set Q for terminal constraints is of finite co-dimensional in the space X. Later, this result was generalized to the case of mixed constraints and to other evolution systems (Li and Yong, 1991; Yong, 1993). Existence theory of optimal control was studied by Yong(1992).

It is well-known that if the optimal value function is smooth enough, then relationships between the maximum principle and the dynamic programming can be established. In the case where the value function is not smooth, such relationships can also be established in the sense of viscosity solutions, whatever the system is of finite dimensional (Zhou, 1990) or infinite dimensional (Li and Yong, 1995).

For the LQ control problem of infinite dimensional systems, when the input operator is bounded and the weighting operator in the cost is indefinite, the optimal feedback control was given by You (1983) via the Fredholm integral equation, from which the Riccati integral equation can be deduced. Later, the equivalence between the Fredholm integral equation and the Riccati integral equation was established directly (Chen,S.P.,1985). For LQ control problems with both unbounded input operator and indefinite criterion, a detailed treatment can found in the book by Li and Yong (1995). The LQ optimal control problem for a class of systems governed by eigen-equations in the Hilbert space was discussed by Feng and Zhu (1984). Approximation problems and singular control problems were discussed in (Feng and Ding, 1989; Zhang and Feng, 1995).

7.2 *Boundary Control*

Consider the boundary control problem of the following nonuniform wave equation:

$$\begin{cases} u_{tt} - \sum_{i,j=1}^{n} \frac{\partial}{\partial x_i}(a_{ij}(x)\frac{\partial u}{\partial x_j}) = 0, \; x \in \Omega, \; t > 0 \\ u|_{\Gamma_1} = 0, \; u|_{\Gamma_0} = v, \; t > 0, \\ u(0,x) = \phi_0(x), u_t(0,x) = \phi_1(x), x \in \Omega. \end{cases}$$

where the matrix $(a_{ij}(x))_{n\times n}$ is symmetric and positively definite on $\mathbb{R}^n$. By introducing a Riemannian geometric approach, Yao (1995) tackled an open problem posed by J.L.Lions in 1988 concerning the exact controllability of the above equation. Yao's geometric approach made it possible to extend various previous results on boundary control of uniform systems to nonuniform systems by giving checkable geometric conditions (cf.e.g., Lasiecka et al., 1997).

Besides, feedback stabilization of wave equations and Timoshenko beams with boundary dissipation was considered in (Zhang and Feng, 1996; Feng and Zhang, 1998). Energy decay properties of various boundary feedback control systems for elastic beams and string vibrations were investigated in (Luo and Guo, 1997; Guo and Zhu, 1997).

7.3 *Stability, Stabilization and Pole-Placement*

For linear systems in Hilbert spaces

$$\dot{x}(t) = Ax(t)$$

where A is the infinitesimal generating operator of some C_0 semi-group $T(t)$, Huang (1985), independent of the western scholars, proved that the necessary and sufficient condition for exponential stability of the above system is $i\mathbb{R} \subset \rho(A)$ and

$$\sup_{\omega\in\mathbb{R}} \|(i\omega - A)^{-1}\| < \infty.$$

Furthermore, Huang and Liu (1987) showed that the characteristics of the exponential stability can be described by a certain L_p-integrability. Other characterizations of exponential stability were studied in (Yao and Feng, 1994; Luo and Feng, 1998; Guo, 1998). The connection between exponential stabilizability and controllability was given in (Liu, 1997). Yao and Feng(1996) expounded the definition domain and the structure characteristics of the square root of unbounded nonnegative operators in Hilbert spaces. Necessary and sufficient conditions for solvability of pole-placement problems together with the related formula were extensively studied in the early 80s (e.g., Wang et al.,1982; Feng and Zhu, 1982; Liu, 1982).

7.4 *Population Systems*

China is country with the largest population in the world, it is therefore of special importance to study population systems.

The dynamic process of population evolution in a country or a region can be described by the following first order partial differential equation (Song and Yu, 1981, 1988):

$$\begin{cases} \dfrac{\partial p(a,t)}{\partial t} + \dfrac{\partial p(a,t)}{\partial a} = -\mu(a,t)p(a,t) + g(a,t) \\ p(a,t_0) = p_0(a) \\ p(0,t) = \beta(t) \displaystyle\int_{a_1}^{a_2} k(a,t)h(a,t)p(a,t)da \\ N(t) = \displaystyle\int_0^{a_m} p(a,t)da \end{cases}$$

where $N(t)$ denotes the population size at time t, $p(a,t)$ is the population density function of age a at time t, $\mu(a,t)$ is the mortality rate, $g(a,t)$ is the migration rate, $\beta(t)$ denotes the total fertility rate (TFR) — the average number of child bearings per female throughout her life, $k(a,t)$ is the female proportion function and $h(a,t)$ is the female fertility pattern. All these quantities can be determined by the population census data.

As noted by Song and Yu (1988) the above is a controllable system with boundary positive feedback, and the TFR $\beta(t)$ is just the control parameter, which can be used to adjust the population size and the age structure. Moreover, Song and Yu (1981) and Song (1982) found that under certain conditions there exists a critical value β_{cr} of $\beta(t)$

$$\beta_{cr} = \left(\int_0^\infty k(a)h(a)e^{-\int_0^a \mu(\rho)d\rho}da\right)^{-1}$$

such that as $t \longrightarrow \infty$ the population size $N(t)$ satisfies

$$N(t) \longrightarrow \begin{cases} \infty, & \text{if } \beta(t) > \beta_{cr} \\ 0, & \text{if } \beta(t) < \beta_{cr} \\ c(t_0), & \text{if } \beta(t) = \beta_{cr} \end{cases}$$

Based on China's population census data in 1982, the critical value of TFR for the country was estimated to be $\beta_{cr} = 2.16$, and the following prediction for China's population growth trend was made and announced: If China kept its 1975 birth rate (TFR=3.0), then the country's population would surpass the then world total in 100 years period of time (Song and Yu, 1988). This announcement shocked the scientific circle and politicians , and many people suggested that China should follow a policy of "one child system"(TFR = 1.0)(Song, 1995). This policy was accepted by the Chinese Government in the early 80s and was relaxed a bit later on (Song, 1995). According to statistics, the TFR in 1997 was about 1.8, which is considerably smaller than the critical value 2.16 of the China's population system. If the present policy will be followed, China's population will be kept under 1.5–1.6 billion by the mid of the next century.

8. DISCRETE- EVENT / MANUFACTURING SYSTEMS

8.1 *Discrete- Event Dynamical Systems (DEDS)*

For linear DEDS described by maximum algebra, Chen and Qi(1995) obtained the necessary and sufficient condition for arbitrary periodic-assignment by feedback; Zheng and Wang (1989) studied the asymptotic performance and robustness of DEDS under parameter perturbations; and Zhao and Zheng (1997) presented a systematic study of problems concerning finite test for robustness of event-driven time series in the presence of interval parameter-perturbations and gave a Kharitonov-like criterion. The applications of the DEDS theory were hampered to a large extent by the model's high dimensions and the unusual operations. In view of this, a solution-finding mechanization method was investigated (Xiao and Xu, 1998).

Jiang(1996, 1997) studied the Petri-net models of DEDS, provided a classification of computation capabilities and a proof of their equivalence. He also discussed the concept of dynamic invariance together with its algebraic criterion. By combining the macro-functioning DEDS represented by Petri-nets and the micro-functioning CVDS, Xu et al.(1997) described a typical class of hybrid systems. For a class of flexible manufacturing systems modeled by Petri-nets, Xing (1996) gave a deadlock avoidance control policy, implementable by Petri-nets.

For optimal service control of a serial production line with n failure-prone workstations and random demand, Song and Sun(1998) showed that the optimal policy is of bang-bang type and can be described by a set of switching manifolds. For stochastic production lines described by linear dynamic equations over Max-algebra, Tu and Sun(1993) obtained the gradient estimates directly by using a local analytic expression of the performance. For unreliable manufacturing systems with general probability distributions, Tu et al.(1997) proposed a preventive hedging point control policy with the optimal hedging parameters being estimated by the method of perturbation analysis

8.2 *Contemporary Integrated Manufacturing Systems(CIMS)*

CIMS is one the main themes of China's High-Tech Research & Development Program (called 863 Program). Thirteen years have been past since this program was put into effect in 1987. Started from the concept of computer integrated manufacturing, experienced the research and practice of information integration, process re-engineering and optimization and enterprise integration, the concept of contemporary integrated manufacturing systems (CIMS) was finally put forward(cf. Wu and Li, 1998). In the past years, a mainline throughout the research and development of CIMS in China has been the systematology. The coordinated developments and mutual permeation of multi-disciplines and the close combination of theory with practice are clear-cut features of CIMS in China (Wu and Li, 1998).

The applications of CIMS have achieved considerable success in China. In around 1990, CIMS was first implemented in Chengdu Aircraft Industrial Co., Shenyang Blower Works and Beijing No.1 Machine Tool Plant, etc. Several years later, significant economic benefits were gained. Up to now, CIMS has been popularized in about 150 plants distributed in about 20 provinces and autonomous regions in China, which has contributed to the developments of various sized enterprises.

The CIMS Engineering Research Center at Tsinghua University received the "University LEAD Award" from the Society of Manufacturing Engineers (SME) of U. S. in 1984, and one year later, the Beijing No.1 Machine Tool Plant received the SME "Industrial LEAD Award".

9. CONCLUDING REMARKS

The past twenty years has been witnessed as the best period for the development of science and technology in the recent history of China. During this period, considerable advances have been made in both theory and applications of automatic control and the related systems science, of which this paper only takes a snapshot in several major areas in the Chinese mainland.

As exemplified in the paper, systems and control science is of special importance to China:

- China has a large population and vast territory, but the cultivated areas and natural resources are relatively poor. There are a wealth of problems concerning with the efficient utilization of natural resources, the preservation of ecological environments, and the healthy developments of social and population systems, etc., for which the systems and control science can indeed offer a helpful hand.

- China is a developing country with weak industrial infrastructure. Systems and control science has a great potentiality and a vast background in reforming and revitalizing the traditional industries and enhancing the competence of enterprises.

Finally, we would like to remark that *control* and *system* are coexistent, however, we are still lack of comprehensive theoretical understandings of many practical systems such as economical, biological and social systems, etc. Initiated by Dr.Tsien, such open complex giant systems have attracted research interests in China since the beginning of the 90s (cf. Tsien et al., 1990). It is conceivable that, in next century, systems and control scientists will inevitably face the challenges of designing "intelligent" controls for more and more complex systems.

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