This paper proposes a methodology for the synthesis of nonlinear robust output feedback controllers for systems of quasi-linear parabolic partial differential equations with time-varying uncertain variables. The method is successfully applied to a typical diffusion-reaction process with uncertainty.

A linear matrix inequality approach to decentralized control of distributed parameter systems

D’Andrea, Raffaello

In this paper, preliminary results in the use of linear matrix inequalities for the decentralized control of distributed parameter systems is presented. The class of systems being considered are those that can be expressed as multidimensional systems. It is shown that linear matrix inequalities can be used to provide tractable solutions to this problem; the conditions are in general conservative, but are computationally attractive and lead to controllers which have a decentralized structure. An example is included to demonstrate the validity of this approach.

Nonlinear control of Navier-Stokes equations

Christofides, Panagiotis D.
Armou, Antonios

This paper proposes a methodology for the synthesis of nonlinear finite-dimensional feedback controllers for incompressible Newtonian fluid flows described by two-dimensional Navier-Stokes equations. The method is successfully applied to Burger’s equation.

Thermal distribution control in scanned processing of materials

Fourligkas, Nikolaos V.
Doumanidis, Charalabos

Scan thermal processing, enabled by guidance of the heat source trajectory during fabrication, combines the flexibility of sequential methods to the productivity of parallel processes. For cylindrically symmetric parts, this is performed by their rapid revolution under a radially or axially translated torch. The source power is modulated to implement a specified thermal distribution as it sweeps the product surface, and thus to generate desirable material features. An analytical description of the thermal field, based on superposition of Greens functions, is developed for off-line analysis. Also, a multivariable model with least-squares parameter identification, is introduced for real-time compensation of the process efficiency. This model is embedded to a thermal distribution control scheme, driving the scanned torch motion and power by a simulated annealing optimization strategy. This uses temperature feedback from random surface locations by an infrared pyrometer. The thermal regulator is validated computationally and experimentally, and its applicability to other scanned processes is examined.

Model reduction for a tungsten chemical vapor deposition system

Chang, Hsiao-Yung
Adomatilis, Raymond A.

A model of a tungsten chemical vapor deposition (CVD) system is developed to study the CVD system thermal dynamics and wafer temperature nonuniformities during a processing cycle. We develop a model for heat transfer in the system’s wafer/susceptor/guard ring assembly and discretize the modeling equation with a multiple-grid, nonlinear collocation technique. This weighted residual method is based on the assumption that the system’s dynamics are governed by a small number of modes and that the remaining modes are slaved to the slow modes. Our numerical technique produces a model that is effectively reduced in its dynamical dimension, while retaining the resolution required for the wafer assembly model. The numerical technique is implemented with only moderately more effort than the traditional collocation or pseudospectral techniques. Furthermore, by formulating the technique in terms of a collocation procedure, the relationship between temperature measurements made on the wafer and the simulator results produced with the reduced-order model remain clear.

A performance limitation of tracking controller for SIMO distributed parameter systems

Yoon, Myung-Gon
Kang, Ji-Yoon

An optimal H-infinity single-input multi-output tracking problem is studied for distributed parameter system. It is shown that the performance of optimal tracking controller have severe limitations due to the distributed nature of system. As a case study we design a tracking controller for flexible beam where control objectives are both tip position tracking and deflection suppression.

Issues in cold start emission control for automotive IC engines

Sun, Jing
Sivashankar, N.

In this paper, we consider the problem of reducing unburned tailpipe hydrocarbon (HC) emissions for internal combustion engines during the “cold start” period. Using pareto-optimization and a cold start engine and catalyst model, the trade-offs between rapid catalyst “light-off” and reduction in unburned HC will be analyzed. The effects of different operating constraints and catalyst light-off characteristics on the optimization results will also be discussed.

Comparative analysis of closed loop AFR control during cold start

Leisenring, William
Yurkovich, Stephen

This paper examines the air-fuel ratio (AFR) control of the spark-ignited, internal combustion engine during cold start. It has been shown that a significant amount of emissions occur during cold start and idle before the AFR closed-loop control system goes into effect. Use of combustion pressure feedback, as measured from within the engine cylinder, is investigated for AFR control during cold start in an attempt to achieve better emissions. Specifically, the combustion pressure is used to calculate the Equivalent Heat Release Duration (EHRD), which is then used for feedback control. Linear and nonlinear control techniques are applied to a Ford V8 engine in a laboratory setting, and the results are compared.

Control of variable geometry turbocharged diesel engines for reduced emissions

Stefanopoulou, A. G.
Kolmanovsky, Ilya V.
Freudenberg, James S.

A multivariable control scheme is designed to minimize emission of nitrogen oxides (NOx) and generation of smoke during rapid acceleration commands in a Diesel engine equipped with variable geometry turbocharger (VGT) and external exhaust gas recirculation system (EGR). Steady-state optimization results in operating points where NOx emissions and smoke generation are highly coupled and require joint management by VGT and EGR actuators.
This paper addresses a problem of controlling diesel engines equipped with a variable geometry turbocharger and an exhaust gas recirculation valve. The presence of two actuators and nonlinear behavior of the system makes the problem difficult to handle using classical control designs. Instead, we employ a recently developed control Lyapunov function (CLF) based design method that guarantees a robustness property interpretable as gain and phase margins. The controller has been tested in simulations and experimentally in the dynamometer test cell.

Coordination of engine and transmission using hybrid control methodologies
Beydoun, Ali
Wang, Le Yi
Ford Motor Co.
Wayne State Univ.

Automotive powertrain systems represent an important class of practical hybrid systems which are characterized by the following features: (1) The systems are inherently hybrid, i.e., hybrid control is not merely a choice. This is exemplified by transmission gear positions (discrete) and engine throttle control (analog). (2) System dynamics are highly nonlinear and contain parametric errors and structural uncertainties. In this paper, a hybrid control design approach is used to develop control strategies for coordination of automotive engine and transmission systems. The main goal is to achieve driving performance, fuel economy, and robustness, with emission as a constraint. The design procedure follows closely the main ideas of the method for robust hybrid control introduced recently by Wang, Khargonekar and Beydoun. The method employs performance indices in guiding both analog and discrete control actions such that robust stability and performance of closed-loop hybrid systems are maintained in the presence of modeling errors, disturbances, and structural uncertainties. The method is further modified to accommodate practical constraints, including actuator saturations, gear shifting limitations, and real-time computation requirements.

Damping of idle engine speed oscillations using a reversible alternator
Gokcek, Cevat
Kabamba, Pierre T.
Univ. of Michigan
Univ. of Michigan

We consider the problem of damping the speed oscillations of an automotive engine crankshaft using a reversible alternator, with a focus on the design of the controller. The reversible alternator is used to apply a control torque to the crankshaft that will improve the uniformity of its speed. One would then potentially use a lighter flywheel, or remove it altogether, thereby reducing engine size and weight. We have characterized the controllers that meet a variety of possibly competing performance specifications, leading to design charts. These charts are level curves of various controller performance metrics in a two-dimensional plane of controller design parameters. Simulation results suggest that engine speed oscillations can be substantially reduced by this method.

Nonlinear control of hypersonic flight with neural networks
Grohs, J. R.
Balakrishnan, S. N.
Univ. of Missouri
Univ. of Missouri

Application of reinforcement learning to dexterous robot control
Bucak, Ilsham Omur
Zohdy, Mohamed A.
Oakland Univ.
Oakland Univ.

In this paper, we consider the use of reinforcement learning for control of nonlinear dexterous robot. The control problem dictates that the learning is performed on-line, based on a binary reinforcement signal from a critic without knowing the system nonlinearity. The learning algorithm consists of an action and critic units that learned to keep multifinger hand of the dexterous robot within expected limits. The multifinger hand is based on “artificial muscle” concept, whereby the hand receives a probabilistic reinforcement signal (reward or penalty) and selects best control actions. The objective is to apply forces so as to keep the finger within the limits of the angular position and velocity at each link. The nonlinear sigmoidal transfer function has been chosen for replacing the original discontinuous binary threshold function during the learning rule evaluation.

Neural-network-inverse-model control strategy: discrete-time analysis for relative order one system
Hussain, Mohamed A.
Univ. of Malaya

In this work, we describe a framework for the stability analysis of the neural-network-inverse-model control strategy for a relative order one system. This is performed by representing the closed loop system in state space and applying Lyapunov’s analysis to study its stability behaviour. The results shows that the stability region lies within a ball. Simulation studies are also performed to complement the stability analysis on a two-tank-in-series system.

Controlling the transition from stable resting to tracking control of an unstable system
Yang, Pai-Hsueh
Australander, David M.
Univ. of California at Berkeley
Univ. of California at Berkeley

Fuzzy transition logic is used to select control modes for launching an unstable system from its resting state on a mechanical hard stop. A “soft tracking” algorithm is used to manage the process of stabilization immediately following launch. The control has been applied to an experimental system consisting of a hydraulically balanced beam pivoted at its center and open-loop unstable.

Fuzzy adaptive control based on RBFN
Chen, Xiaohong
Wu, Qidi
Qian, Jixin
Tongji Univ.
Tongji Univ.
Zhejiang Univ.

Aiming at the practical plants with strong nonlinear characteristics or changing operating points, this paper develops a fuzzy adaptive control strategy based on RBFN, continuing the work in papers [1,2]. Theoretically, neural networks can approximate any given sample sets accurately, but an industrial plant is often highly non-linear or with changing operating points. It is very difficult to approximate such a plant by only one neural network. On the other hand, the multi-model method brings about the oscillation problem. The control strategy proposed in this paper possesses not only the performance of high accuracy like that of multi-model method, but also eliminates the disadvantages of multi-model method. Simulation results to a pH CSTR demonstrate the above properties.
A recently developed new paradigm for probabilistic robustness analysis does not require a priori information about the underlying distribution function for the uncertain parameters; only a mild monotonicity and symmetry assumption is involved. The starting point is exactly the same as in classical robustness theory -- a system with uncertain parameters which are only known within given bounds. However, instead of calculating the classical robustness margin for such a system, a risk-adjusted margin is sought. The theory suggests that the “best” way to sample the uncertain parameters is not necessarily the most intuitive way. That is, the sampling distribution to use is not something obvious such as a normal or uniform distribution. The main objective of this paper is to demonstrate that these “counterintuitive” predictions of the theory are not just mathematical possibilities but actually admit physical realizations.

In this paper, we extend the existing order statistics distribution theory to the general case in which the order statistics is associated with certain constraints and the distribution of population is not assumed to be absolutely continuous. In particular, we derive an inequality on distribution for related order statistics. Moreover, we also propose two different approaches in searching reliable solutions to the robust stability and optimal synthesis problems under constraints. Furthermore, minimum computational effort is investigated and bounds for sample size are derived.

Developing uncertainty models suitable for modern robust design methods involves numerous modeling decisions regarding uncertainty structure, noise models and uncertainty bounds. In this paper, we consider the problem of selecting between one of two candidate uncertainty models based on input-output data. Each uncertainty model consists of a nominal linear plant with a standard linear fractional transformation (LFT) uncertainty structure and Gaussian output noise. A classical statistical hypothesis testing performance measure is used to evaluate decision procedures. We derive a D-scaled upper bound on this performance measure, and show that this upper bound can be minimized by convex programming and H-infinity filtering techniques. In addition, a general robust hypothesis testing result is derived.

A systematic method for determining the Nyquist robust stability margin for a polynomial subject to ellipsoidal parametric uncertainty is presented. The margin is calculated as the infinity norm of a stable, minimum-phase transfer function whose frequency response magnitude characterizes the robust stability of the system. The appropriate transfer function is constructed directly from elements of the nominal polynomial and the matrix describing the uncertainty ellipsoid.

In this paper we show that the solvability of the strengthened robust SPR problem is more stringent in the discrete-time case than in the continuous-time case. A necessary condition is provided for the solvability of the strengthened robust SPR problem, which discards the search for a compensator: in some important adaptive schemes used for identification purposes.

This paper describes a graphical evaluation of the robust stability in a frequency domain based on the results from our previous paper in which the extension of Popov’s criterion to discrete-time systems was expressed in an explicit form. The control system described herein is a sampled-data control system with one time-invariant nonlinear element (sector nonlinearity) in the forward path. Considering the application to a computer-aided control system design (CACSD), we will present an evaluation method of the robust stability in connection with the size of sector nonlinearity and the gain margin on a gain-phase diagram (i.e., a modified Nichols chart). We will show two results as numerical examples: one is where Azerman’s conjecture was approved, and the other is where it was not.

Two anti-windup algorithms, the Optimal Set-Point Sequence algorithm (OSSA) and the Simplified Set-Point Sequence algorithm (SSSA), are presented in this paper to deal with the problem of controller windup and the subsequent degradation in output performance as a result of set-point changes. These algorithms are computationally simple and extremely effective. The proposed anti-windup algorithms use an understanding of the causes of the problem in order to prevent the problem from occurring or minimizing it in the first place. We have shown through simulations, and where possible through experimental verifications, that the results are applicable to single-input single-output, and multiple-input multiple-output processes.

This paper deals with asymptotic tracking of linear systems subjected to actuator saturation. Both reference inputs and disturbances are assumed to belong to a class which may be regarded as the zero-input response of a linear system. The controller includes an anti-windup term which reduces the degradation in the system performance due to saturation. The stability of the overall system is established based on the Lyapunov stability theory. The proposed scheme is evaluated for a two axis motion control system by simulation.

This paper deals with simultaneous global external and global internal stabilization of critically unstable linear systems with saturating actuators. The paper proposes a new family of scheduled low-and-high gain state
feedback laws that yields a closed-loop system which is both globally finite gain L-p stable and globally asymptotically stable. Moreover, the controller has an explicit design parameter that can be adjusted to make the L-p gain of the closed-loop system arbitrarily small.

TA05-4 1468
Actuator amplitude saturation control for systems with exogenous disturbances
Kapila, Vikram
Polytechnic Univ.
Haddad, Wassim M.
Georgia Inst. of Tech.

In this paper we develop fixed-order (i.e., full- and reduced-order) controllers for systems with actuator amplitude constraints and exogenous bounded energy L2 disturbances. The actuator amplitude saturation and disturbance rejection constraints are embedded within an optimization problem by constructing a Riccati equation whose solution guarantees closed-loop global asymptotic stability in the face of sector bounded input nonlinearities and non-expansivity (gain boundedness) of the input-output system energy. Application of the proposed framework is demonstrated via a numerical example.

TA05-5 1473
Control synthesis versus saturation compensation for systems with rate and amplitude constraints
Hui, K., Chan, C. W.
Univ. of Hong Kong

A control synthesis theory was proposed by Horowitz to design a 'three degrees of freedom' controller for rate and amplitude constrained systems. Following anti-reset windup techniques, a saturation compensation structure was proposed to design compensators for given linear controllers. It is shown here that the compensator can be reformulated in terms of the control synthesis theory. Conversely, the 'three degrees of freedom' controller is a special case of the compensator construction. From this analysis, shortcomings of the control synthesis theory are exposed and improvements using the compensator structure are discussed and illustrated by an example.

TA05-6 1478
Open-loop and feedback bounded control in linear systems
Mikhalev, S. A.
Univ. of Wuppertal

The classical PID regulators technique gives infinite control time duration and the constraints usually imposed on control do not take into consideration. The saturating linear feedback (SLF) meets the imposed control constraints but the control time is also infinite and the known difficulties restrict implementation of SLF. From the other hand it is known that time-optimal bounded control steers the system to the terminal state in finite time. However, it is not easy to fabricate switching surface if the dimension of the system is high. Therefore in most application, the time-optimal feedback has not been used. Remarkable rarities are some space application. In this paper we attempt to design nonlinear bounded feedback that from one hand gives the finite control time duration and from other hand is not complicated. This technique provides the control with the following properties: the control is presented in closed-loop form, can be calculated on-line, and meet the imposed constraints, the control is, to some degree, suboptimal and robust. The talk ends with the example to illustrate the proposed control technique.

TA06-1 1480
Direct adaptive control for tonal disturbance rejection
Zhang, Youping
United Technologies Research Ctr.
Mehta, Prashant G.
United Technologies Research Ctr.
Bitmead, Robert B.
Australian National Univ.
Johnson, C. Richard, Jr.
Cornell Univ.

In this paper, the problem of tonal disturbance rejection via direct adaptive control is considered. The key problem feature is compared with the usual adaptive tracking problem. Traditional model reference and pole placement approaches are attempted, and their advantages and drawbacks are given. We then propose an adaptive solution based on a new parameterization scheme which is unique to the given problem. Simulation studies are used to compare these different schemes.

TA06-2 1488
Adaptive control of multivariable nonlinear systems with application to a large segmented reflector
Kosmatopoulos, Elias B.
Univ. of Southern California
Boussalis, H.
California State Univ.
Miriani, Majed
California State Univ.
Ioannou, Petros A.
Univ. of Southern California

Nonlinear dynamics and modelling uncertainties of a frictional force can cause instability in an adaptive friction compensation scheme. We propose an adaptive nonlinear controller where the persistent excitation in the desired trajectory enables stability of the closed-loop system when the friction force effects are due to static, Coulomb and viscous components, as well as for inertia and the Stribeck effects. The controller is shown to be robust to uncertainties due to frictional lag and frictional memory. Stable adaptation for the nonlinearly-occurring Stribeck parameter is achieved by exploiting convexity/concavity properties. An analytical framework is given to explain the effectiveness of either in friction control problems.

TA06-3 1488
Adaptive control techniques for friction compensation
Feemster, M.
Clemson Univ.
Vedagarbha, Praveen
Clemson Univ.
Dawson, Darren M.
Clemson Univ.
Haste, D.
Clemson Univ.

In this paper, we design two adaptive controllers for a second-order mechanical system which incorporates frictional effects such as Coulomb, static, Stribeck, and viscous friction. First, we design a modular position tracking controller that can accommodate a variety of adaptive update laws. The proposed controller is shown to compensate for uncertainty associated with the friction parameters which appear linearly in the model. In the second control scheme, we show how a Lyapunov-based adaptive position setpoint controller can be designed to compensate for parametric uncertainty throughout the mechanical system including the Stribeck effect related constant which does not appear linearly in the model. Experimental results are provided to illustrate the performance of the proposed controllers.

TA06-5 1493
A frequency response based adaptive control for center-driven web winders
Liu, Zhijun
Rockwell Automation

A frequency response based adaptive control scheme with robust frequency-domain specifications for an industrial center-driven web winder is presented in this paper. The adaptive control scheme consists of: 1) a self-tuning initialization, 2) an adaptive control based on the transfer function estimation from frequency responses, and 3) supervisory monitoring and controls. In the paper, the system modeling is first investigated. Then the adaptive control scheme is described. Finally the simulation results are discussed and implementation issues are addressed.

TA06-6 1495
A globally-stable adaptive field-oriented controller for current-fed induction motors
Ahmed-Ali, Tarek
CNRS Lamnabhi-Lagarrigue, Francoise
Ecole Superieure D'Electricite
Ortega, Romeo S.
SUPELEC

In this short paper we propose a procedure to adjust on-line the rotor time constant estimate of an indirect field-oriented control law for
current-fed induction machines. The resulting scheme is shown to be globally exponentially stable provided the load torque on the motor is zero and the a priori uncertainty on the range of variation of the rotor time constant is smaller than 100%. The latter is a reasonable assumption in many practical cases. We also show that, when the load torque is different from zero, the speed error enters in finite time a residual set whose size is proportional to the load torque.

TA07-1 (I) 1503
Exact slow-fast decomposition of the Hamilton-Jacobi equation of singularly perturbed systems
Fridman, E. M.
Tel-Aviv Univ.

We study a Hamilton-Jacobi partial differential equation, arising in optimal control problem for an affine nonlinear singularly perturbed system. This equation is solvable iff there exists a special invariant manifold of the corresponding Hamiltonian system. We obtain exact slow-fast decomposition of the Hamiltonian system and of the special invariant manifold into the slow and the fast ones. We get sufficient conditions for the solvability of the Hamilton-Jacobi equation in terms of the reduced-order slow subsystem, or in the hyperbolic case, in terms of a reduced-order slow Riccati equation. On the basis of this decomposition we construct asymptotic expansions of the optimal state-feedback, optimal trajectory and optimal open-loop control in the powers of a small parameter.

TA07-2 (I) 1508
Sliding surface design for singularly perturbed systems
Su, Wu-Chung
National Chung-Hsing Univ.

The equilibrium manifold of a singularly perturbed system has a close relationship with the sliding surface of a variable structure system (VSS). The fast time and slow time responses has a similar behavior to the "reaching mode" and "sliding mode", respectively. This paper aims to equip the powerful composite control method with robustness through variable structure control design. The major bridge in between is a Lyapunov function. It is found that a singularly perturbed system in sliding mode may preserve two-time-scale attribute, in which a new equilibrium manifold exists on the sliding surface. Sliding motions being attracted to the manifold can therefore be referred to as "sliding mode in sliding mode".

TA07-3 (I) 1513
Recursive approach to Nash games of quasi singularly perturbed linear systems
Skataric, D.
Univ. of Belgrade
Petrovic, B.
Univ. of Belgrade

In this paper we derive an algorithm for solving the linear-quadratic differential Nash game problem of singularly perturbed systems. It is known that the general steady state solution to the above problem is given in terms of the ill-conditioned coupled algebraic Riccati equations. We show that for a special class, so called quasi singularly perturbed systems, the positive definite stabilizing solutions of the coupled Nash algebraic Riccati equations can be obtained in terms of reduced-order well-conditioned algebraic equations corresponding to slow and fast variables.

TA07-4 (I) 1518
Eigenvector approach for optimal control of singularly perturbed and weakly coupled linear systems
Kecman, Vojislav
Univ. of Auckland
Bingulac, Stanoe
Kuwait Univ.

In this paper we show how to exactly decompose both the singularly perturbed (SP) and the weakly coupled (WC) algebraic Riccati equation (ARE) and the corresponding linear-quadratic optimal control problem at steady state in terms of reduced-order subproblems by using the eigenvector approach. The proposed algorithms may be applied for standard and nonstandard SP systems (as well as for regular linear control systems). The eigenvector approach should be used for decomposition of the SP (WC) control system in the cases when the perturbation (coupling) parameter epsilon is not sufficiently small. In such cases the decomposition methods based on series expansions, fixed point iterations and Newton iterations, either fail to produce solutions of the corresponding algebraic equations or display very slow convergence. By using duality between the linear-quadratic optimal control and the Kalman filtering, the results reported in this paper can also be applied for reduced-order Kalman filtering problems of both singularly perturbed and regular linear stochastic systems. In addition, the eigenvector approach provides new tools and novel insight into the nature of the decomposition problem and finds all required solutions without solving the corresponding subsystem Riccati equations.

TA07-5 (I) 1523
Transformations for decomposition of linear singularly perturbed systems with N-fast subsystems
Lim, Myo-Taeg
Korea Univ.

In this paper we introduce a transformation for exact decomposition (block-diagonalization) of linear singularly perturbed systems composed of one slow and N-fast subsystems. The transformation is very useful for parallel processing of information and computations on parallel computers.

TA07-6 (I) 1526
Recent advances in singularly perturbed control systems – high accuracy techniques
Shen, X.
Univ. of Waterloo

In this paper we give a summary of main results obtained in the context of singularly perturbed linear control systems within the last ten years with emphasis on recursive approach, exact closed-loop decomposition transformation (Hamiltonian approach), and integral manifold theory - high accuracy techniques. In addition, we indicate the recent results obtained for H-infinity optimal control and filtering, jump parameter linear systems, control of robots, stability bounds, Markov chains, and nonlinear singularly perturbed systems.

TA08-1 1531
On optimal robust disturbance minimization
Djouadi, M. S.
Wayne State Univ.
Zames, George
McGill Univ.

In this article, we give an explicit solution to the nonstandard H-infinity problem which includes the Optimal Robust Disturbance Attenuation Problem (ORDAP) and the Two-Disc Problem. Our solution depends on an interplay between function theory, Banach space duality and operator theory. The solution depends on an operator which is analogous to the Sarason operator for the standard H-infinity problem. This operator allows to quantify the optimal performance of feedback systems and provides an explicit formula for the optimal controller. The nonstandard H-infinity problem is perhaps the simplest control problem which deals with significant plant uncertainty. Surprisingly, relatively little work has been done on it despite the large number of papers in the H-infinity control literature.

TA08-2 1536
Solutions to general H-infinity almost disturbance decoupling problem with measurement feedback and internal stability
Chen, Ben M.
National Univ. of Singapore
Lin, Zongli
Univ. of Virginia
Hang, Chang Chieh
National Univ. of Singapore

In this paper, explicitly parameterized control laws are constructed to solve the well-known H-infinity almost disturbance decoupling problem with measurement feedback and with internal stability for continuous-time linear systems. The problem considered is general and complete in that the system is allowed to have invariant zeros on the imaginary axis.

TA08-3 1541
Explicit solvability conditions for a class of disturbance decoupling problems with static measurement feedback

...
A new disturbance rejection scheme for hard disk drive control

A design technique is proposed for disturbance attenuation for polytopic linear parameter-varying (LPV) systems with bounded inputs. The sufficient conditions for feasibility are expressed in terms of matrix inequalities. Both parameter-independent and parameter-dependent controller are considered. The issue of rate constraint is also discussed.

A new disturbance rejection scheme is developed for hard disk drive servo control. The control scheme overcomes the drawback of typical internal-model-based repetitive control schemes which cancel repeatable disturbances but amplify disturbances at other frequencies. More importantly, the proposed scheme is capable of selectively attenuating disturbances at given frequencies without requiring a high order control structure. As a result, it has the ability of rejecting disturbances without a long learning delay which is yet another disadvantage of typical internal-model-based repetitive control schemes. Two ways of designing such a disturbance rejection controller are proposed. Simulations using disturbances constructed from real drive position error signals (PES) have been carried out to show the effectiveness of this control scheme.

By measuring the positions and motions of stars very precisely, the Space Interferometry Mission (SIM) will produce a wealth of new astronomical data and serve as a technology pathfinder for future astrophysics missions providing a leap forward in space based astronomy beyond the Hubble Space Telescope. SIM will present unprecedented challenges in the measurement and control of distributed optical surfaces mounted on precision space structures, hence driving the technological state-of-the-art in the areas of alignment and stabilization of optical-mechanical systems, and deployable structures, vibration isolation and suppression, laser metrology, and the integration and autonomous operation of complex systems. The precise tolerance required by the SIM instrument facilitates the investigation of many design options, trades, and methods for minimizing interaction between the actively controlled optics and the structure. This paper provides an overview of the multidisciplinary integrated modeling methodology for SIM that encompasses the optics, structures, dynamics, and control disciplines within a common software environment. Such integrated models are used at the Jet Propulsion Laboratory for system requirements trade studies, performance analysis and predictions, and control law design for the mission. The modeling methodology is rooted in a closely tied validation program which is necessary to alleviate the paradox of modeling a spacecraft that does not yet exist. The highest fidelity integrated SIM model to date, examples of utility, and incorporation into the overall instrument design are highlighted.

This paper gives an overview of the Micro-precision Interferometer (MPI) testbed and its major achievements to date related to mitigating risk for future spaceborne optical interferometer missions. The MPI testbed is a ground-based hardware model of a future spaceborne interferometer. The three primary objectives of the testbed are to: (1) demonstrate the 10 nm positional stability requirement in the ambient lab disturbance environment, (2) predict whether the 10 nm positional stability requirement can be achieved in the anticipated on-orbit disturbance environment, and (3) validate integrated modeling tools that will ultimately be used to design the actual space missions. This paper presents results which represent the latest advancements made on the testbed in the first two areas. Encouraging results from this testbed confirm that MPI provides an essential link between the extensive ongoing ground-based interferometer technology development activities and the technology needs of future spaceborne optical interferometers.

This paper gives an overview of the Micro-Precision Interferometer (MPI) testbed and its major achievements to date related to mitigating risk for future spaceborne optical interferometer missions. The MPI testbed is a ground-based hardware model of a future spaceborne interferometer. The three primary objectives of the testbed are to: (1) demonstrate the 10 nm positional stability requirement in the ambient lab disturbance environment, (2) predict whether the 10 nm positional stability requirement can be achieved in the anticipated on-orbit disturbance environment, and (3) validate integrated modeling tools that will ultimately be used to design the actual space missions. This paper presents results which represent the latest advancements made on the testbed in the first two areas. Encouraging results from this testbed confirm that MPI provides an essential link between the extensive ongoing ground-based interferometer technology development activities and the technology needs of future spaceborne optical interferometers.

Disturbance analyses during early design phases of high-performance optical systems are usually conducted on nominal point designs. Performance assessment and resource allocation are based on the analysis results even though structural and disturbance models are initially crude and contain significant errors. Confidence in design margins can be increased if bounds due to uncertainties are placed on performance predictions. This paper describes different types of disturbance analyses and shows the insight provided by a frequency-domain disturbance analysis. Exact sensitivity calculations with respect to open-loop modal parameters are derived, and a method for uncertainty analysis is presented for the special case of uncertain modal parameters. Uncertainty propagation is specified as a constrained optimization problem. A large order integrated model of one Space Interferometry Mission concept demonstrates the framework.

Formation sensing and control technologies for a separated spacecraft interferometer
This paper describes spacecraft formation control and sensing research with application to a Separated Spacecraft interferometer. A multi-layer control design that achieves very accurate alignment between spacecraft is described. Sensing for this control architecture is based on a global real-time relative position and orientation estimator that uses Carrier Differential-phase GPS measurements. A local optical sensor is used as well. The experiments are performed on a fully functional indoor GPS environment using three prototype spacecraft on a granite table. Work continues on extending the control to a formation of three active vehicles and on extending the sensing system to a self-configuration.

**TA09-5 (I)**

**Fuel equalized retargeting for separated spacecraft interferometry**

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McLain, Timothy W. Brigham Young Univ.
Hadaegh, Fred Y. Jet Propulsion Lab

Motivated by NASA's proposed Deep Space 3 interferometer mission, this paper considers the problem of reorienting a constellation of spacecraft such that the total fuel distributed across the constellation is both conserved and expended uniformly. The spacecraft constellation is controlled to reorient as if it were a rigid body. Two approaches to fuel equalization are investigated. The first approach picks a point of rotation, a priori, that optimizes an objective function that trades off minimum fuel maneuvers and maneuvers that equalize the fuel. Since the point of rotation is selected a priori and is fixed during the rotation, this approach is open-loop in that it cannot adjust to unpredicted, or inaccurately modeled fuel use. The second approach is closed-loop in that the point of rotation is caused to have second order dynamics that track the center of fuel mass. Intuitively, the center of fuel mass will dynamically change to be close to spacecraft that are low on fuel. Simulation results for a four spacecraft constellation restricted to a plane are given.

**TA09-6 (I)**

**Advanced fringe tracking algorithms for low-light level ground-based Stellar interferometry**

Padilla, Carlos E. Moldyn, Inc.
Karlov, Valeri I. Moldyn, Inc.
Matson, Leslie Moldyn, Inc.
Chun, Hon M. Moldyn, Inc.

Advanced nonlinear fringe tracking algorithms are used to improve the state-of-the-art in ground-based optical stellar interferometric fringe tracking by allowing the tracking of stars one to two bolometric magnitudes dimmer than currently possible. Even more significantly, we demonstrate active fringe locking for dim stars with less than 10% loss of lock probability. Enabling fringe locking through the atmosphere for dim stars has significant implications for ground-based interferometric stellar imaging. These results are a consequence of the powerful estimation framework in which the Discrete Bayesian Algorithm (DBA) is developed. This framework makes it possible to incorporate all the available nonlinear model and statistical information, including the known statistics of atmospheric variations, into the tracking algorithm and thus results in the highest performing fringe tracker. In this work we made use of Zernike polynomial representations in order both to simulate atmospheric variations for algorithm evaluation and comparison, and also to incorporate the atmospheric information into the statistical mechanism of the nonlinear filters developed. All simulations are performed using parameters for the CHARA Array of Georgia State University. The formulation of the DBA for ground-based fringe tracking is presented. The nature of the data structures in the DBA makes it especially well suited to the incorporation of experimental data. A detailed formulation and preliminary evaluation is carried out on the Variation-Invariant Subspace Tracking Algorithm (VISTA). VISTA offers the possibility of making the interferometric measurements invariant to atmospheric disturbances through the optimal projection of many "sub-aperture interferometers" onto one invariant subspace. The DBA can fringe lock dim stars with a 50% loss of lock probability where state-of-the-art fringe tracking techniques fail. The use of VISTA in the fringe locking regime resulted in an improvement on the DBA results by up to one bolometric magnitude dimmer stars. This is made possible by the increased visibility resulting from making the fringe measurements invariant to tip/tilt Zernike modes in the atmospheric phase variations.

**TA10-1 (I)**

**Actuator fault detection and isolation in nonlinear systems using LMIs and LMEs**

Yaz, Edwin E. Univ. of Arkansas
Azemi, Asad Penn State Univ. - Del. Cty.

An actuator fault detection and isolation scheme for a class of continuous-time nonlinear systems is presented. A bank of unknown-input observers is used for this purpose. Only linear matrix equations and inequalities are used in the design which makes it particularly attractive from a computational viewpoint.

**TA10-2 (I)**

**Innovation generation for bilinear systems: application to robust fault detection**

Kinnnaert, Michel Univ. Libre de Bruxelles

An algorithm to design an innovation generator for bilinear systems with unknown inputs is presented. Such a generator is a filter which, in the absence of faults, generates a zero-mean white noise sequence, called innovation, from the known inputs and the outputs of the monitored system. The innovation sequence can then be processed by statistical tests to decide whether a fault has occurred or not. The choice of the test depends on the nature of the faults (additive or nonadditive faults).

**TA10-3 (I)**

**Nonlinear rule-based detection and identification of control system failures**

Schram, G. Delft Univ. of Tech.
Gopisetty, S. M. Princeton Univ.
Stengel, Robert F. Princeton Univ.

Well-established linear procedures for detection and identification of control system failures are extended to nonlinear systems within a fuzzy logic framework. This rule-based approach has particular advantages for application to nonlinear systems that can be represented as linear parameter varying (LPV) systems. The effectiveness of the technique in the presence of modeling uncertainties, actuator dynamic failures and failures in redundant actuators is evaluated. It is pointed out that for certain practical failures, identification of the exact failure is a limitation that existing approaches to failure detection and identification do not address. Use of additional sources of information and a knowledge-based diagnostics is highlighted. Simulations conducted on a nonlinear aircraft model are included.

**TA10-4 (I)**

**Fault detection and isolation for nonlinear processes based on local linear fuzzy models and parameter estimation**

Balle, Peter Tech. Univ. of Darmstadt
Isermann, Rolf Tech. Univ. of Darmstadt

In this contribution, a new approach for model-based fault detection and diagnosis (FDI) of sensor and process faults for nonlinear processes is presented. A fuzzy model (Takagi-Sugeno type) of the nominal process provides characteristic features like time constants and static gains in the actual region of operation. Comparing these with features derived by recursive parameter estimation leads to significant symptoms which indicate the state of the system. The practical applicability is illustrated on an industrial scale thermal plant. Here, nine different faults can be detected and isolated continuously over all ranges of operation.
This paper discusses the development of a numerical tool that determines the dynamic horizontal control effector sizing criteria for given High Speed Civil Transport dynamic model. This criteria includes computing the maximum cg travel for a range of control effector sizes and actuator motion constraints, while guaranteeing an existence of a feedback controller that will recover from a severe gust without exceeding actuator amplitude and rate limits and satisfy other dynamic requirements. The key idea is to formulate these constraints in terms of Linear Matrix Inequalities. This tool is termed the Tail Sizing Design Tool. In addition, the paper illustrates the application of the tool to measuring the effect of adding a second horizontal control surface in the form of a canard. The capability to measure the effect of simple, symmetric, flexible motion of the vehicle is also addressed. Based on numerical analysis of designs, conclusions are drawn on the relative effectiveness of the use of canards, the use of static versus dynamic controllers, and on the inclusion of aeroelastic effects.
This paper presents three controllers that globally stabilize a benchmark nonlinear system. Neither affine in control nor of triangular structure, the system is not in a class to which existing constructive methodologies are applicable.

TA12-2
Stability margins in inverse optimal input-to-state stabilization
Krstic, Miroslav
Univ. of California at San Diego

We show that if a system is input-to-state stabilizable, one can always design a controller that is input-to-state stabilizing in the presence of input unmodeled dynamics of the form $a(I+P)$ where $a > 1/2$ is constant and $P$ is a strictly passive (possibly nonlinear) system. This result is a direct extension to nonlinear systems with disturbances of the well known inverse optimality result for linear systems (infinite gain margin and 60 degrees phase margin).

TA12-3
Stabilization under measurement noise: Lyapunov characterization
Ledyzav, Yuli S.
Western Michigan Univ.
Sonntag, Eduardo D.
Rutgers Univ.

For systems affine in controls, Artstein's theorem provides an equivalence, between continuous feedback stabilizability to an equilibrium and the existence of smooth control Lyapunov functions. This is one of the fundamental facts in nonlinear stabilization. The equivalence breaks down for general nonlinear systems, not affine in controls. One of the main results in this paper states that the existence of smooth Lyapunov functions implies the existence of, in general discontinuous, feedback stabilizers which are insensitive (or robust) to small errors in state measurements. Conversely, the existence of such stabilizers in turn implies the existence of smooth control Lyapunov functions. In a more general framework of systems under persistently acting disturbances, the existence of smooth Lyapunov functions turns out to be equivalent to the existence of (in general, discontinuous) feedback stabilizers which are robust with respect to small measurement errors and small additive external disturbances.

TA12-4
State-dependent Riccati equation solution of the toy nonlinear optimal control problem
Hull, Richard A.
Coleman Research Corp.
Cloutier, James R.
WL-MNAG
Mraček, Curtis P.
WL-MNAG
Stansbery, Donald T.
QuesTech, Inc.

The SDRE approach to optimal control has been shown in previous studies to be a systematic design technique for a broad class of nonlinear regulator problems. In this paper we examine the "toy nonlinear" optimal control problem posed as a counter-example to the SDRE method, and presented by Doyle and Packard in the nonlinear control workshop at the 1997 American Control Conference. We first review the SDRE design technique, and the conditions required to assure local asymptotic stability of the method. We show that applying SDRE to the toy nonlinear problem using a single parameterization may fail to produce a stable solution. Examining the problem in detail, we determine those characteristics which pose difficulty for the SDRE technique, and propose solutions for each. We then demonstrate that by choosing an appropriate parameterization for this problem, and by adding a stabilizing term to the system dynamics in the controller design equation, the SDRE method generates a well behaved solution of this problem.

TA12-5
Semi-global robust nonlinear control: state-dependent scaling and computational aspects
Ito, Hiroshi
Kyushu Inst. of Tech.

This paper develops a computationally tractable approach to the analysis and synthesis problem of robust control of nonlinear systems with structured gain-bounded uncertainty. It is shown how state-dependence of scaling matrices can be utilized to reduce the conservatism of nonlinear systems analysis and synthesis. The robust performance problem with state-dependent scaling is characterized by linear matrix inequalities. This paper clarifies to what degree these LMI conditions can actually guarantee robustness of the nonlinear system. Furthermore, the controller synthesis problem of expanding the region where required performance is achieved is formulated as a convex optimization.

TA12-6
Nonlinear system stabilization via equilibria-dependent Lyapunov functions: beyond gain scheduling control
Leonnessa, Alexander
Georgia Inst. of Tech.
Haddad, Wassim M.
Georgia Inst. of Tech.
Chellaboina, Vijaya-Sekhar
Georgia Inst. of Tech.

In this paper a novel Lyapunov-based nonlinear control design framework guaranteeing stability for a parameterized set of system equilibria is developed. Specifically, using equilibria-dependent Lyapunov functions we construct a nonlinear control strategy that stabilizes a given nonlinear system and additionally provides an explicit expression for a guaranteed domain of attraction. The proposed framework provides a rigorous foundation for designing gain scheduled feedback controllers guaranteeing closed-loop system stability over a range of system operating conditions.

TA13-1 (I)
Nonlinear stability-constrained model predictive control with input and state constraints
Cheng, Xu
Westinghouse Electric Corp.
Krogh, Bruce H.
Carnegie Mellon Univ.

In stability-constrained model predictive control (SCMPC) a stability constraint is propagated from stage to stage to limit the magnitude of the state vector in a controllable form. For the unconstrained case, a sufficient condition that can be easily evaluated guarantees the stability constraint is a feasible contraction mapping. This paper presents sufficient conditions for guaranteed asymptotic stability when SCMPC is applied to nonlinear systems with arbitrary constraints on the control and state.

TA13-2 (I)
Stability analysis for linear/nonlinear model predictive control of constrained processes
Valluri, Sairam
Drexel Univ.
Kapila, Vikram
Polytechnic Univ.

In this paper, we present a stability analysis method for input constrained SISO linear/nonlinear systems with model predictive controllers. Specifically, this method is based on a Lyapunov function framework and provides a subset of the domain of attraction for the closed-loop stability under the shortest-prediction-horizon model predictive control laws. By using this framework a designer can a posteriori verify the overall stability of closed-loop system for a desired performance in the event of actuator saturation. The effectiveness of the method is demonstrated by considering linear and nonlinear examples.

TA13-3 (I)
On feedback linearization in LMI-based nonlinear MPC
van den Boom, Ton J. J.
Delft Univ. of Tech.

Feedback linearization has proven to be very valuable in nonlinear predictive control. It is, however, only applicable to a small class of systems and it has the drawback of degrading the original performance index. In this paper an approximate feedback linearization technique makes it possible to extend the method to a wider class of nonlinear systems. A recovery of the original performance index is suggested, all in an LMI-based setting. Finally, tuning the feedback linearization parameters can be important to obtain optimal robustness. A simulation example shows the effect of the performance index recovery and different parameter settings.

TA13-4 (I)
Bilinear matrix inequalities and robust stability of nonlinear multi-model MPC

This is one of the fundamental facts in nonlinear stabilization. The existence of smooth Lyapunov functions implies the existence of, in general discontinuous, feedback stabilizers which are insensitive (or robust) to small errors in state measurements. Conversely, the existence of such stabilizers in turn implies the existence of smooth control Lyapunov functions. In a more general framework of systems under persistently acting disturbances, the existence of smooth Lyapunov functions turns out to be equivalent to the existence of (in general, discontinuous) feedback stabilizers which are robust with respect to small measurement errors and small additive external disturbances.

TA12-3
Stabilization under measurement noise: Lyapunov characterization
Ledyzav, Yuli S.
Western Michigan Univ.
Sonntag, Eduardo D.
Rutgers Univ.

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TA12-4
State-dependent Riccati equation solution of the toy nonlinear optimal control problem
Hull, Richard A.
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The SDRE approach to optimal control has been shown in previous studies to be a systematic design technique for a broad class of nonlinear regulator problems. In this paper we examine the "toy nonlinear" optimal control problem posed as a counter-example to the SDRE method, and presented by Doyle and Packard in the nonlinear control workshop at the 1997 American Control Conference. We first review the SDRE design technique, and the conditions required to assure local asymptotic stability of the method. We show that applying SDRE to the toy nonlinear problem using a single parameterization may fail to produce a stable solution. Examining the problem in detail, we determine those characteristics which pose difficulty for the SDRE technique, and propose solutions for each. We then demonstrate that by choosing an appropriate parameterization for this problem, and by adding a stabilizing term to the system dynamics in the controller design equation, the SDRE method generates a well behaved solution of this problem.

TA12-5
Semi-global robust nonlinear control: state-dependent scaling and computational aspects
Ito, Hiroshi
Kyushu Inst. of Tech.

This paper develops a computationally tractable approach to the analysis and synthesis problem of robust control of nonlinear systems with structured gain-bounded uncertainty. It is shown how state-dependence of scaling matrices can be utilized to reduce the conservatism of nonlinear systems analysis and synthesis. The robust performance problem with state-dependent scaling is characterized by linear matrix inequalities. This paper clarifies to what degree these LMI conditions can actually guarantee robustness of the nonlinear system. Furthermore, the controller synthesis problem of expanding the region where required performance is achieved is formulated as a convex optimization.
A BMI-based approach to an on-line computationally efficient robust nonlinear MPC is proposed. Theoretical results and a simple example accompany the proposed method.

**TA13-5**

Model predictive control for on-line optimization of semi-batch reactors

Heilig, A. RWTH Aachen
Abel, O. RWTH Aachen
Marquardt, Wolfgang RWTH Aachen

In practical situations the knowledge on discontinuous reaction processes as well as the available measurement information is often very limited. Usually this renders the application of model based methods for recipe design and off-line re-optimization impossible. On the other hand, several important variables can be estimated on-line allowing a short range prediction of the process behavior. This paper discusses on-line recipe optimization of semibatch reactors for such an industrial scenario. The derived concept is based on reaction calorimetry for vapor-liquid systems and formulated in the framework of Model Predictive Control (MPC). In simulation studies of an industrial semibatch polymerization reactor the MPC for on-line optimization yields exactly the same operational profiles as an off-line optimization using a detailed process model.

**TA13-6**

Nonlinear model predictive control of the Tennessee Eastman process

Zheng, Alex Univ. of Massachusetts

The main purposes of this paper are to illustrate several key issues in the implementation of a conventional Nonlinear Model Predictive Control algorithm on a reasonably large industrial process and to test the effectiveness of the Nonlinear Model Predictive Control algorithm recently proposed by Zheng for control of large nonlinear systems with constraints. We show why a conventional Nonlinear Model Predictive Control algorithm may fail to provide integral control under very reasonable conditions (i.e., integral control is guaranteed if and only if a global solution is implemented and the output horizon is infinite) and illustrate this undesirable behavior through simulations on the Tennessee Eastman process. In addition to computational advantage, we argue that Zheng’s algorithm may be preferred based on robust performance consideration.

**TA14-1**

Hybrid power systems with diesel and wind turbine generation

Bialasiewicz, Jan T. National Renewable Energy Lab.
Droulhet, S. National Renewable Energy Lab.
Nix, G. National Renewable Energy Lab.

In this paper, we present a modular simulation system developed to study the dynamics and to aid in the design of hybrid power systems with diesel and wind turbine generation. The emphasis is placed on the representation of the dynamics of the elements of a real system and on the control aspects of the modules. The system developed is especially useful when a new configuration of a power system is to be analyzed, a new load or wind speed profile has to be included, additional modules have been installed in an existing power system, or an old control strategy is to be replaced by a new one.

**TA14-2**

Application of proportional-integral and disturbance accommodating control to variable speed variable pitch horizontal axis wind turbines

Kendall, Lewis Univ. of Colorado at Boulder
Balas, Mark J. Univ. of Colorado at Boulder
Lee, Yung Jae Univ. of Colorado at Boulder
Fingersh, Lee Jay Univ. of Colorado at Boulder

A variable-speed, constant-pitch wind turbine was investigated to evaluate the feasibility of constraining its rotor speed and power output without the benefit of active aerodynamic control devices. A strategy was postulated to control rotational speed by specifying the demanded generator torque. By controlling rotor speed in relation to wind speed, the aerodynamic power extracted by the blades from the wind was manipulated. Specifically, the blades were caused to stall in high winds. In low and moderate winds, the demanded generator torque and the resulting rotor speed were controlled to cause the wind turbine to operate near maximum efficiency. A computational model was developed, and simulations were conducted of operation in high turbulent winds. Results indicated that rotor speed and power output were well regulated.

**TA14-4**

Wind turbine control system modeling capabilities

Pierce, Kirk National Renewable Energy Lab.
Fingersh, Lee Jay Univ. of Colorado at Boulder

This work examines the memory-based method for variable speed control of wind turbines. The main idea behind this approach is to use certain gathered information such as past and recent rotor speed as well as previous control experience to generate new control action. Both theoretical and simulation studies show that this method is able to ensure stable tracking of rotor speed under modeling uncertainties and external disturbances.

**TA14-6**

Dynamics and control of structural loads of wind turbines

Ekelund, Thommy Chalmers Univ. of Tech.

The potential for active attenuation of structural dynamic load-oscillations, by means of continuous control of the yaw servo, is investigated in this study. The analysis is based on a model with flexibly interconnected rigid bodies. The focus is put on the tower bending, particularly in the lateral direction. The results show the importance of the yaw stiffness for the lateral tower-bending. Furthermore, in the particular case studied here, a periodic LQ controller could achieve the same lateral damping as a suspension system with a spring and damper, or PD controller, with less than 10% of the tower torsion. The results clearly indicate the importance of considering the system’s periodic dependence on time in the controller design.

**TA15-1**

Robust filtering in an intercept system

Cong, Shan Wright State Univ.
Hong, Lang Wright State Univ.

In this paper, robust filtering theory is applied to the estimation problem in an intercept system. First, the intercept system is analyzed. A robust filtering problem is formulated for missile seekers. The design of robust filters is also discussed in this paper. A design example is given to illustrate how the new technique can improve the performance of an intercept system.

**TA15-3**

Stabilizability of an antagonistic biomimetic actuator system

Kolacinski, Richard M. Case Western Reserve Univ.
Lin, Wei Case Western Reserve Univ.
Chizeck, Howard Case Western Reserve Univ.

A BMI-based approach to an on-line computationally efficient robust nonlinear MPC is proposed. Theoretical results and a simple example accompany the proposed method.
We investigate the problem of asymptotic stabilization of a biomimetic actuation system which independently modulates position and net stiffness. We show how the passivity formalism and the technique of input saturation can be used to Globally Asymptotically Stabilize (GAS) this mechanical system via bounded feedback. The performance of the proposed stabilizing controller is illustrated through a numerical simulation.

TA15-4 1732
Stability analysis of a missile control system with a dynamic inversion controller

Schumacher, Corey
Wright Lab.
Khargonekar, Pramod P.
Univ. of Michigan

This paper examines the closed-loop stability of a bank-to-turn, air-to-air missile with a dynamic inversion controller using a two time-scale separation assumption. A state-space formulation for the alpha, beta, and phi dynamics of the missile, assuming the inner-loop dynamic inversion is performed exactly, is presented. It is then shown that, under certain assumptions, the exponential stability of the alpha, beta, and phi dynamics about the commanded values can be guaranteed if the inner loop design frequency is large enough. An example calculation of the required inner-loop frequency to guarantee stability is done for a particular bank-to-turn missile. Finally, nonlinear six degree-of-freedom simulation results of a maneuver performed with the dynamic inversion controller are presented.

TA15-5 1737
Guaranteed cost control of stochastic uncertain systems applied to a problem of missile autopilot design

Petersen, Ian R.
Australian Defense Force Academy

In this paper, we apply a recent result on output feedback guaranteed cost control of stochastic uncertain systems to the problem of designing a missile autopilot. In the missile autopilot design problem, the given data is a finite collection of plant models for the missile corresponding to different flight conditions. A total least squares approach is used to fit the data to a norm bounded uncertain system model.

TA15-6 1742
Model based leakage detection in a pulverized coal injection vessel

Johansson, Andreas
Lulea Univ. of Tech.
Medvedev, Alexander V.
Lulea Univ. of Tech.

A method for detecting and isolating incipient leakages in the valves of a pulverized coal injection vessel for a blast furnace process is presented. Non-linear physical gray-box models of the plant are developed. Values of the unknown parameters are estimated by identification. Observers are constructed for these models and the residuals are used in a Generalized Likelihood Ratio test. The method is successfully tested with real leakages intentionally introduced in the plant.

TA16-1 (I) 1747
Modelling, calibration, and control-theoretic analysis of the GMAW process

Moore, Kevin L.
Idaho State Univ.
Yender, R.
Idaho State Univ.
Tyler, J.
Idaho State Univ.
Naidu, D. Subbaram
Idaho State Univ.

In this paper we discuss the gas metal arc welding control problem. We give an overview of the problem. We then describe both an analytical and an experimental model of the process. We conclude with experimental results of single-input, single-output and multi-loop control strategies applied to the process.

TA16-2 (I)
In process optimization of gas metal arc welding parameters

Smartt, H. B
Lockheed Martin Idaho Tech. Co.
Johnson, J. A.
Lockheed Martin Idaho Tech. Co.

TA16-3 (I)
Interval model based control of gas metal arc welding

Zhang, Y. M.
Univ. of Kentucky
Liguo, E.
Univ. of Kentucky
Walcott, Bruce L.
Univ. of Kentucky

A control system is developed to control pulsed gas metal arc welding process. To guarantee the desired metal transfer mode, i.e., one-drop per-pulse, the welding current is switched from the peak level to the background level so that an oscillation of the droplet is excited up. When the droplet moves downwards, the welding current is switched back to the peak level. The combination of the downward momentum of the oscillating droplet and the increased electromagnetic force guarantees that the droplet be detached. Instead of the duration of the background current, the waveform of the welding current is adjusted to control the melting rate of the electrode wire so that the metal transfer frequency can keep constant during welding. To simplify the control system, the ranges of the welding operational parameters are used to quantify the uncertainty in the dynamic model of the welding process. Based on the uncertainty range of the dynamic model, a single control algorithm has been developed to handle different operational parameters. Experiments confirmed effectiveness of the developed system.

TA16-4 (I)
Feedback linearization control of current and arc length in GMAW systems

Abdelrahman, Mohamed A.
Tennessee Tech. Univ.

In this paper we design a model based nonlinear controller for a GMAW system. The controller uses nonlinear state feedback to exactly linearize and decouple the GMAW system. The linearized system is then controlled using 2-PI controllers. The effect of parameters uncertainty over the closed loop system performance is investigated and simulations that show the system performance are presented.

TA16-5 (I)
Application of MIMO direct adaptive control to gas metal arc welding

Ozcelik, Selahattin
Texas A&M Univ. at Kingsville
Moore, Kevin L.
Idaho State Univ.
Naidu, D. Subbaram
Idaho State Univ.

This paper presents the design of a Direct Model Reference Adaptive Control (DMRAC) for a Gas Metal Arc Welding Process (GMAW). Recently developed highly nonlinear fifth order mathematical model for the GMAW process is used. Simplications and linearization yield the process to be modeled as two-input two-output second order system. Current and arc voltage as being the process outputs are controlled by open circuit voltage and wire feed speed, which are chosen as the process control inputs. Considering wide range of operating conditions, process parameters are allowed to vary within their prescribed ranges. The stability analysis for this interval process is performed using Kharitonov’s theorem. Simulations are performed on the fifth order nonlinear process and satisfactory results are obtained.

TA16-6 (I)
An animated MATLAB/SIMULINK tool for gas metal arc welding control experimentation

Ozcelik, Selahattin
Texas A&M Univ. at Kingsville

This paper details the simulation and animation package developed for a Gas Metal Arc Welding Process (GMAW) in the Measurement and Control Engineering Research Center (MCERC) of Idaho State University (ISU). This package is developed using MATLAB-SIMULINK, a numerical analysis software.

TA17-1 (I)
Control applications and challenges in air traffic management

Jackson, Joseph W.
Honeywell Inc.
Green, Steven M.
NASA Ames Research Center
This tutorial paper describes the current air traffic management, provides a notional description of the future "Free Flight" concept of airspace operations, and presents several control applications and challenges in air traffic management that are of interest to the controls community.

**TA17-2 (I) 1789**

**Analysis of pilot intent parameters in air traffic management**

Zhao, Yuyuan  
Univ. of Minnesota

Haissig, Christine  
Honeywell Tech. Center

Hoffman, Mary Jo  
Honeywell Tech. Center

The current air traffic control infrastructure specifies detailed flight procedures for commercial airliners. Due to heavy traffic intensity and the mixture of IFR and VFR traffic at major airports, there have been several near-miss scenarios and some major mid-air collisions. Development of airborne collision avoidance system becomes necessary, and it has been realized that exchange of pilot flight intents is highly beneficial to resolving conflicts. In the proposed free flight environment, aircraft operators can alter their flight plans in real time without a priori approval of ground controllers, and it is crucial for aircraft operators to communicate their intentions to ground controllers and to other aircraft operators. This paper lists several groups of parameters that can potentially be used as intent parameters. Merits of these parameters are discussed. Distinctions are made between short term intents for tactical conflict avoidance, and long term intents for flow management.

**TA17-3 (I) 1793**

**Aerodynamic envelope protection using hybrid control**

Tomlin, Claire J.  
Univ. of California at Berkeley

Lygeros, John  
Univ. of California at Berkeley

Sastry, Shankar S.  
Univ. of California at Berkeley

This paper presents the application of controller synthesis for hybrid systems to aerodynamic envelope protection and safe switching between flight modes. Each flight mode, which describes a configuration of the dynamic equations describing the motion of the aircraft, is treated as a discrete state with associated continuous, nonlinear dynamics and the safe subset of the state space (that which ensures aerodynamic envelope protection) is calculated for each discrete state. The methodology is applied to a longitudinal axis model of a CTOL aircraft.

**TA17-4 (I) 1797**

**Robust optimization methodologies for the free route concept**

El Ghaoui, Laurent M.  
ENSTA

Seigneuret, Franck  
ENSTA

Recently, a new technique called robust optimization has been proposed for addressing (dynamic) decision problems with uncertainty. This approach starts from a "nominal" optimization problem, say a linear program. Assuming bounds, and structure, of the uncertainty are known, we seek a robust solution, that is, one which minimizes the (worst-case) objective while satisfying the constraints robustly. Such solutions can be approximately computed in modest computing time, using Lagrangian relaxations and convex optimization. The method is computationally cheaper than stochastic programming, yet produces guarantees (that constraints are satisfied despite uncertainty). This paper outlines some potential applications of the method to robust collision detection in the context of free route.

**TA17-5 (I) 1800**

**Modeling of an airline operations control center as a queuing network**

Pujeta, Nicolas  
Massachusetts Inst. of Tech.

Feron, Eric  
Massachusetts Inst. of Tech.

Rakhit, Ananda  
United Airlines

A discrete event model for multi-agent real-time process control is introduced in the context of United Airlines' Operations Control Center (OCC). The model represents the OCC agents as a network of queuing servers, and organizes the individual communication and decision tasks into discrete event processes flowing through this queuing network. The input to the agent network is the superposition of a deterministic periodic demand, a stochastic demand and an uncertain forecast of future demand. The identification of the dynamic characteristics of each agent in the network is carried out through a combination of on-site measurements and statistical analysis of transactional data. A computer simulation of this OCC model is presented.

**TM01-1**

**Neural network based tracking control of flexible joint manipulators**

Efrati, T  
Univ. of Southern California

Flashner, Henryk  
Univ. of Southern California

A new control strategy for trajectory tracking of the tips of the flexible-link manipulators is presented. The control law utilizes only easily obtainable quantities: joint angles and their rates, endpoint deflections of each link and their rates. The control law is an optimal switching rule between a conventional PD controller and a new nonlinear controller, which is developed for the planar, multi-link elastic manipulator case. The stability of the controller is proved using LaSalle's theorem. The results are compared with a conventional PD controller for a single-link flexible manipulator. The simulation results indicate that the proposed controller performs much better than the conventional PD controller with the same proportional and differential gain set.

**TM01-3**

**Closed loop stability analysis of a flexible robot arm using feedback control**

Zhang, Rongjun  
Purdue Univ. at Indianapolis

Chen, Yaobin  
Purdue Univ. at Indianapolis

Sun, Zengqi  
Tsinghua Univ.

Sun, Fuchun  
Tsinghua Univ.

This paper presents a new strategy for stability analysis of feedback controlled flexible arm without truncation. The unconstrained modal analysis method is used to derive a set of infinite dimensional ordinary differential equations (ODEs) with rigidity-flexibility decoupled. Based on this set of ODEs, matrix factorization and its relevant techniques are employed to analyze the closed-loop stability of the system under feedback control. Several common feedback controlled systems were studied. Validation through comparative and experimental studies is presented.

**TM01-4**

**Optimal position controller of a two-link flexible-joint robot manipulator**

Lahdhir, Tarek  
Univ. of Windsor

ElMaraghy, Hoda A.  
Univ. of Windsor

This paper presents the design of an optimal nonlinear position tracking controller for a two-link flexible joint robot manipulator. The controller is designed based on the concept of exact feedback linearization and LQG/LTR techniques. It is shown that the nonlinear robot model is feedback linearizable and a characterization of the set, over which the linearizing transformation is diffeomorphic, is provided. The proposed control approach reduces the number of required measurement sensors and takes into account the effects of measurement noises. Also, a new method for computing the nonlinear state estimate is presented. This method takes advantage of the linear structure of the transformed system. Simulation results demonstrate the potential benefits of the proposed control approach in reaching the desired performance with minimum control effort and equipment.

**TM01-5**

**Comparison of linear and nonlinear H-infinity control for a flexible-link manipulator**
In a flexible-link manipulator, in general the effect of some parameters such as payload, friction amplitude and damping coefficients cannot be exactly measured. In this paper, constant as well as L-2 bounded deviations of parameters from their nominal values are considered as uncertainties. These uncertainties make it difficult for a linear controller to achieve desired closed-loop performance. Based on recent results in nonlinear H-infinity control a nonlinear controller is designed for the flexible-link manipulator. It is shown that the nonlinear controller has a larger domain of attraction than the linearized controller.

This paper presents a modal feedback controller for vibration control of multi-link flexible robots. The controller is based on independent joint PD control and modal feedback. The asymptotic stability of the proposed control scheme has been proved via Lyapunov stability theory. Both the design procedure and the implementation of the controller are simple. Simulation results confirm the good performance of the controller.

The design of optimal desired traffic flow patterns for multiple lanes Automated Highway Systems (AHS) is analyzed. A highway network model, which is based on the notion of activity and a principle of vehicles conservation, is proposed. The traffic flow pattern for the network of highways is found in such a way that the total entry flow to the AHS network is maximized and the constraints related to the dynamic highway model and the AHS capacity are simultaneously satisfied.

We consider that freeway traffic flows out onto surface streets and surface street traffic flows into freeways and thus the combined performance of both freeway and surface street portions of a network are interrelated. We analyze a control architecture to improve surface street flow using adaptive signal controllers and introduce an important component towards coordinating control of surface street networks with freeway control. The contribution of this paper relates to the use of a particular adaptive signal control scheme at each intersection called ALLONS-D and a description of how to impart directives from a higher level controller to these local controllers such that traffic performance on the whole is maximized. Our result is a multi-layer approach for controlling the infrastructure in an urban street network. Simulations on an arterial network and a grid network are performed to test the coordination procedure that is presented.

This paper investigates development of onboard road departure warning systems. A new approach, called the variable rumble strip (VRBS), is proposed. It is an onboard electronic implementation of the static rumble strip where the warning threshold is allowed to vary according to the risk of vehicle road departure. Performance of the VRBS system is similar to that of the time-to-lane-crossing approach, but requires less sensor information, making it more feasible in a vehicle application. Performance is measured in terms of hits, misses, and false alarms based on a validation warning set comprised of either static rumble strip generated warnings or by subjective interpretation of the road departure critically. The algorithms are tested on two-hour driving simulator runs by 12 drivers.

The design of constrained navigation algorithms for strapdown inertial navigation systems with reduced set of sensors is achieved given sufficient information content in the filtered force vs. slip data. Results confirm applicability of the EKF and Bayesian selection to 1) extracting tire force vs. slip or slip angle data from which tire models can be constructed or verified, and 2) real-time friction estimation. The former task is achievable for a large range of steering and braking inputs and road conditions. The latter task is achievable given sufficient information content in the filtered force vs. slip data.
Automatic design of fuzzy controllers
Wang, Li-Xin Hong Kong Univ. of Science & Tech.

In this paper, we propose to use adaptive fuzzy controller as a mean to generate the rule base of fuzzy controller automatically. Specifically, we run an adaptive fuzzy controller from a number of initial conditions such that the trajectories of these runs cover the domain of interest. Since the adaptive fuzzy controller can automatically generate control parameters along the trajectories, we store these parameters after each run. The final fuzzy rule base is constructed from these stored parameters. Since the trajectories cover the whole domain, the rule base generated is complete. The main advantage of the method is that a complete fuzzy rule base can be generated automatically without domain experts and without mathematical model.

TM03-2 1855
Fuzzy controller design using space-filling curves
Elshafei-Ahmed, M. King Fahd Univ. of Petro. & Minerals
Ahmed, M. S. King Fahd Univ. of Petro. & Minerals

In this paper we present a clustering technique for fuzzy rules based on Hilbert Space-filling Curves (SFC). SFC scans an n-dimensional space and reduces it to a curve, i.e. a one-dimensional line. The paper introduces first the Hilbert space-filling curves, and outlines algorithms for clustering and adaptive clustering which demonstrate the SFC efficient self-organizing features. We then propose a SFC fuzzy inference model based on clustering the object space. The SFC fuzzy model is then used to design a fuzzy controller. The proposed method achieves a dramatic reduction in the complexity of fuzzy controller by reducing the multivariable fuzzification problem to a one dimensional space.

TM03-3 1860
Self-learning fuzzy PID controller based on neural networks
Li, QiQiang Zhejiang Univ.
Cheng, Zhenggun Zhejiang Univ.
Qian, Jixin Zhejiang Univ.

Conventional PID tuner and fuzzy inference systems based on expertise will be in trouble when the expertise of a process is not enough. Artificial neural networks are of self-learning capability, however the change of their weights can not be understood. This paper describes the structures of self-learning neurofuzzy networks and shrinking-span membership functions, and presents a neurofuzzy PID controller (NFPID). The NFPID controller has the capability of self-extracting inference rules, and its parameters have explicitly physical definitions. By using RBFNN inverse model, a hybrid learning procedure was put forward. Variety simulation results demonstrated that the NFPID controller has very good performances.

TM03-4 1862
A study on learning scheme of self-learning rule-based fuzzy controller using random variable sequence
Jeong, Seung-Hyun Yeungnam Univ.
Han, Chang-Wook Yeungnam Univ.
Park, Jung-II Yeungnam Univ.
Kwon, Soon-Hak Yeungnam Univ.

In this paper, a learning scheme for self-learning rule-based fuzzy controller using random variable sequence is proposed. A new adaptive fuzzy controller, in which the width and center of membership functions consisting of fuzzy rule bases are self-organized by the proposed learning scheme, is proposed. The validity of the proposed algorithm is confirmed by applying it to the control of the inverted pendulum.

TM03-5 1864
Designing fuzzy models for nonlinear discrete-time systems with guaranteed performance
Wang, Li-Xin Hong Kong Univ. of Science & Tech.

A weak point of the existing fuzzy or neural approaches to nonlinear system identification and control is that the fuzzy systems or neural networks are viewed as black boxes and their internal structures are not analyzed and used in the design of the system. In this paper, we propose an identification scheme for nonlinear discrete-time systems using fuzzy systems that takes the specific internal structure of the fuzzy system explicitly into consideration. We first design a fuzzy system and give the upper bound of its approximation error to a general nonlinear function. Then we propose a projection algorithm to turn the parameters in the fuzzy identification model and prove that the parameter error is nonincreasing and the identification error converges to an error band which can be made arbitrarily small by properly designing the fuzzy system. We also determine conditions under which the parameters converge.

TM03-6 1866
A fuzzy approach to greenhouse climate control
Caponetto, R. SGS-Thomson Microelectronics
Fortuna, L. Univ. degli Studi di Catania
Nunnari, G. Univ. degli Studi di Catania
Occhipinti, L. SGS-Thomson Microelectronics

The methodology proposed in the paper deals with the use of Artificial Intelligence techniques in the modelling and control of some climate variables within a greenhouse. The non-linear physical phenomena governing the dynamics of temperature and humidity on such systems are, in fact, difficult to be modelled and controlled using traditional techniques. The paper proposes a framework for the development of Fuzzy Logic Controllers (FLCs) in modern greenhouses.

TM04-1 1958
Plotting robust root loci for linear systems with multilinearly parametric uncertainties
Hwang, Chyi National Chung Cheng Univ.
Chen, Jh-Jia National Chung Kung Univ.

This paper deals with the problem of characterizing the boundary of the image of an m-dimensional (m-D) box Q under a multilinear mapping f: Rm → C. We introduce the set of generalized principal points (GPPs) G to construct the value set f(Q). Based on the connectedness property of GPP manifolds, we present a multi-dimensional pivoting procedure with integer labeling to trace out all GPP manifolds. As an application, the presented value-set construction algorithm is applied along with the zero-inclusion principle and a two-dimensional pivoting procedure to characterize the smallest set of regions in the complex plane within which all the roots of a multilinear interval polynomial family lie.

TM04-2 1871
Robustness of pole-retention inside specified regions for interval descriptor systems
Fang, Chun-Hsiung National Kaohsiung Inst. of Tech.
Lu, Chun-Lin National Kaohsiung Inst. of Tech.
Kau, Shih-Wei National Kaohsiung Inst. of Tech.
Hong, Lin National Kaohsiung Inst. of Tech.

A sufficient condition is given to ensure that all finite poles of interval descriptor systems are retained inside specified regions. The proposed criterion also guarantees the robustness of impulse elimination. The merit of the proposed approach is clearly displayed in the calculation of robustness bounds for an uncertain liquid-level control system.

TM04-3 1874
Robust root-clustering analysis in a union of subregions
Bachelier, Olivier LAAS-CNRS
Pradin, B. LAAS-CNRS

This paper addresses the research of robustness bounds for systems described by linear state space models. These bounds on the norm of unstructured uncertainties guarantee that the eigenvalues of the perturbed state matrix remain in a region of the complex plane in which the eigenvalues of the nominal state matrix
lie. The bounds are obtained through a linear matrix inequalities (LMI) approach. This allows to choose not only some special simple convex region (symmetric with respect to the real axis), but also some special non-convex (but symmetric) union of convex subregions, each of them being not necessarily symmetric with respect to the real axis. It can be of interest in the problems of robust design where one wants to specify different regions for dominant and not dominant pole-clustering. This larger choice of regions in the computation of such robustness bounds is an original aspect of the presented work.

**TM04-4** 1879  
Test for nonnegativity of polynomials with literal coefficients by quantifier elimination  
Bose, N. K. Pennsylvania State Univ.  
Charoenlarpnopparut, C. Pennsylvania State Univ.

A systematic scheme that leads to a set of inequalities involving the free variables, whose satisfaction will be necessary and sufficient for global positivity or nonnegativity of any specified polynomial with literal coefficients, is developed.

**TM04-5** 1881  
Model matching approach to discrete time polynomial optimization problems  
Pellegrinetti, Gordon Univ. of Illinois at Urbana-Champaign  
Bentsman, Joseph Univ. of Illinois at Urbana-Champaign

This paper presents a solution to the H-infinity predictive control problem based on minimax prediction using a technique inspired by the solution of the model matching problem. This solution methodology uses a Youla-Kucera parameter to consider only controllers which are in the set of stabilizing controllers. The final form of the equations which define the controller is simplified, resulting in a better numerical solution readily solvable by a generalized eigenvalue problem.

**TM04-6** 1883  
On Sturm’s theorem for interval polynomials  
Okuyama, Yoshifumi Tottori Univ.  
Takehiro, Fumiaki Tottori Univ.  
Chen, Hong Tottori Univ.

The number of characteristic roots in a specified contour on an s-plane can be determined by Sturm’s theorem. In this paper, we will analyze the sequential operations of coefficients based on the division algorithm when the characteristic equation is expressed as an interval polynomial. We will examine whether these operations are reduced to the extreme point results of interval coefficients, give a graphical interpretation of the discrimination method, and give some numerical examples.

**TM05-1** 1886  
Semi-global L2 gain analysis for kth-degree systems based on reachable set analysis  
Sato, Yoko Waseda Univ.  
Watanabe, Ryo Osaka Univ.  
Uchida, Kenko Waseda Univ.

In this paper, we define the kth-degree system which is regarded as Taylor series up to the kth-degree term for the nonlinear system, and propose an analysis technique of the semi-global L2 gains based on the reachable set analysis for the kth-degree systems with the constraint sets on the disturbances. In this technique, the upper bounds of the semi-global L2 gains are obtained by solving linear matrix inequalities. We also illustrate the effectiveness of the proposed method with a numerical example.

**TM05-2** 1889  
Two algorithms arising in analysis of polynomial models  
Nesic, Dragan Univ. of California at Santa Barbara

Algorithms for testing observability and forward accessibility of discrete-time polynomial systems are presented. The algorithms are based on symbolic computation packages - the Groebner basis method and QEPCAD. The observability test checks observability of general polynomial systems in finite time. Forward accessibility test is applicable to a large class of polynomial systems and also stops in finite time.

**TM05-3** 1894  
Analysis of chaotic physical systems and an algorithm for control  
Christensen, Scott R. Oakland Univ.  
Zohdy, Mohamed A. Oakland Univ.

Numerous engineering, physics, meteorology and biomedical systems can be classified as projecting chaotic behavior. This can occur naturally or as a result of the underlying mathematical dynamical equations. In this paper, we consider comprehensive analysis of typical physical systems from several performance viewpoints: the power spectrum, the embedding dimension, Lyapunov exponents, return maps and Poincaré animation. A discussion of a modern control and prediction algorithm follows. Finally, a proposal is made for the laboratory construction of a device to coalesce the analysis, prediction and control schemes on realistic data.

**TM05-4** 1899  
Stability of nonlinear control systems based on low-order block-oriented models  
Harris, Kenneth R. Univ. of California at Davis  
Palazoglu, Ahmet N. Univ. of California at Davis

A method to calculate a region of attraction for controllers based on low-order block-oriented models is presented. The method uses a generalization of the circle criterion, which is less conservative than other input/output stability methods since the shape of the nonlinearity is also considered. The developed method is applied to a simulation example and additional applications are discussed.

**TM05-5** 1904  
Robust stability and performance analysis of systems with hysteresis nonlinearities  
Pare, Thomas E. Stanford Univ.  
How, Jonathan P. Stanford Univ.

There has been extensive work done in recent years on the analysis and synthesis of systems having memoryless, sector bounded nonlinearities and uncertainties. In this paper we take a fundamentally different approach to develop tests of the stability of systems having hysteresis nonlinearities which, in general, have heavy memory and are not sector bounded. Using an operator perspective, and considering a hysteresis that obeys a strict circulation direction, we develop a transformation which converts a hysteresis nonlinearity into a passive operator. Our main stability theorem then provides a simple Nyquist test (for a SISO system) or a linear matrix inequality (LMI) which is extended to include a provision for a robust performance test. A simple numerical example illustrates the benefit of the multiplier introduced for this class of nonlinearities.

**TM05-6** 1909  
On steady-state properties of certain max-plus products  
Shue, Louis Australian National Univ.  
Anderson, Brian D. O. Australian National Univ.  
Dey, Subhrakanti Australian National Univ.

The asymptotic properties of inhomogeneous products in the max-plus algebra context have been investigated. In particular, for products involving matrices with the same unique critical circuit, we have obtained some sufficiency conditions under which the rank of the final product matrix is less than or equal to the length of the critical circuit of the matrices in the product. For a product comprising of matrices with the same unique critical circuit of length 1, the asymptotic rank is 1.

**TM06-1** 1914  
Identification of a fluidized catalytic cracking unit: an orthonormal basis function approach
Multivariable system identification of a model IV fluidized catalytic cracking unit is performed. The system exhibits both fast and slow dynamics, is multivariable and nonlinear. The length of the applied data sets is only two times the settling time of the system which makes the identification of the low frequent behaviour a difficult task. Besides, the identification is complicated by a drift of the measured outputs from the given initial condition to a stationary working point. Identification methods that apply nonlinear optimization techniques are avoided because these get stuck in bad local minima and are time-consuming for the given data. A linear time-invariant model parametrization is applied which is based on orthonormal basis functions. This model structure is a linear regression structure from which results in a simple convex optimization problem for least squares prediction error identification. Unknown initial conditions are estimated simultaneously with the system dynamics to account for the instationarity of the data. The model accuracy for low frequencies is improved by a steady-state constraint on the estimated model and incorporation of prior knowledge of the large time constants in the model structure. The model accuracy is furthermore improved by an iteration over identification of a high-order model and model reduction. First a high order model is estimated using an orthonormal basis. This model is reduced and used to generate a new orthonormal basis which is used in the following iteration step for high order estimation. With the approach followed accurate models over a large frequency range are estimated with only a limited amount of data.

Identification of friction at low velocities using wavelet basis function network

South China University of Technology

Modeling friction at low velocities can be viewed as a problem of characterizing the local behavior of a complex nonlinear function. Wavelet theory provides a very powerful framework for localized mapping and learning. Based on space-frequency localization, a model-free methodology is proposed to identify and compensate for friction at low velocities using a wavelet basis function network (WBFN) based design is proposed and validated using a hardware example case. The methodology is systematic and uses minimal knowledge of the dynamics which is particularly attractive for a large class of dynamic systems with friction.

System identification of a natural gas engine

Northern Illinois University

In this paper, simulation results are shown for linear system identification carried out to identify key model parameters of a lean-burn natural gas engine with transmission. The natural gas engine can be described by a nonlinear plant with three states. The dynamic state equations of the model involve parameters that might vary depending on ambient conditions, type of transmission connected to the engine, and parametric variation from engine to engine. Linear system identification is used around an operating point to identify key parameters of the nonlinear model (e.g. engine/transmission inertia) that can be used to tune linear or nonlinear controllers.

Identification of relative degree

South China University of Technology

This paper presents some algorithms for identifying relative degree of linear time-invariant systems. Various approximate formulas for estimating relative degree are derived based on the relationship between the relative degree and the system’s impulse responses. Bounds on the estimation errors are computed.

Identification of a pressurized tank process is considered in this paper. A subspace identification method is employed that identifies the system in question from the Laguerre spectra of the input/output data. The method is presented in a general form and valid in the continuous and in the discrete-time case. Using the input/output Laguerre spectra for identification, instead of the complete input/output data vectors, leads to a considerable data reduction. Furthermore, it is shown by a simulation study that the subspace identification method n4sid works better in Laguerre domain than in time domain.

A simple recursive algorithm for diagnosis of abrupt changes in signals and systems

University of Technology, Troyes

We address the problem of detecting and isolating abrupt changes in signals and systems with random disturbances. An asymptotic optimal solution to this problem, which has been proposed in previous works, leads to the number of arithmetical operations at time t which grows to infinity with t. Moreover, the proposed criterion of optimality does not impose a constraint on the probability of false isolation when the change time is greater than 1. In this paper we propose another more realistic criterion, establish a new simple recursive change detection/isolation algorithm and investigate its statistical properties. This algorithm can be recommended for on-line implementations.
exponential decay estimates on the transient responses for the systems are presented. All of the results are derived by using Lyapunov function methods. Some stability and stabilization results with respect to time-varying/time-invariant decay degree for some classes of retarded dynamic systems are also presented as the applications of the established conditions. It is revealed that the established estimates can be less conservative than those obtained by only using the sufficient stability conditions in the literature.

**TM07-5**

Numerical computation of cross-covariance functionals for linear systems with multiple time delays

Hwang, Jyh-Haur
National Chung Cheng Univ.

Tsay, Sun-Yuan
National Chung Cheng Univ.

Hwang, Chyi
National Chung Cheng Univ.

**TM07-6**

A delay-dependent robust stability criterion for uncertain time-delay systems

Park, Poogyeon
Pohang Univ. of Science & Tech.

Moon, Young Soo
Seoul National Univ.

Kwon, Wook Hyun
Seoul National Univ.

This paper considers a problem of robust stability of uncertain time-delay systems. Using a new inequality on inner product of two vectors, a new delay-dependent robust stability criterion is presented. It is illustrated by numerical examples that the proposed criterion can be less conservative than the existing stability criteria.

**TM08-1**

Solvability conditions for 4-block H-infinity control problems with infinite and finite jw-axis zeros

Xin, Xin
Tokyo Inst. of Tech.

Mita, Tsutomo
Tokyo Inst. of Tech.

Anderson, Brian D. O.
Australian National Univ.

The 4-block H-infinity control problem with infinite and finite jw-axis is discussed in this paper. Via the eigenstructures related to the infinite and finite jw-zeros, this paper extends the DGKF’s approach to the H-infinity control problem without the constraints on the infinite or finite jw-axis zeros. The necessary and sufficient conditions are proposed for checking its solvability by solving two reduced-order Riccati equations and examining matrix norm conditions related to jw-axis zeros.

**TM08-2**

Parameterization of all controllers for 4-block H-infinity control problems with infinite and finite jw-axis zeros

Anderson, Brian D. O.
Australian National Univ.

Xin, Xin
Tokyo Inst. of Tech.

Mita, Tsutomo
Tokyo Inst. of Tech.

A parameterization is presented of all solutions to the 4-block H-infinity control problem with infinite and finite jw-axis zeros. The parameterization is given in terms of linear fractional transformation (LFT) on stable transfer function matrices with gain less than 1 which are free apart from satisfying certain interpolation conditions.

**TM08-3**

On optimal solutions to two-block H-infinity problems

Hassibi, Babak
Stanford Univ.

Kailath, Thomas
Stanford Univ.

In this paper we obtain a new formula for the minimum achievable disturbance attenuation in two-block H-infinity problems. This new formula has the same structure as the optimal H-infinity norm formula for noncausal problems, except that doubly-infinite (so-called Laurent) operators must be replaced by semi-infinite (so-called Toeplitz) operators. The benefit of the new formula is that it allows us to find explicit expressions for the optimal H-infinity norm in several important cases: the equalization problem (or its dual, the tracking problem), and the problem of filtering signals in additive noise. Furthermore, it leads us to the concepts of “worst-case non-estimability,” corresponding to when causal filters cannot reduce the H-infinity norms from their a priori values, and “worst-case complete estimability,” corresponding to when causal filters offer the same H-infinity performance as noncausal ones. We also obtain an explicit characterization of worst-case non-estimability and study the consequences to the problem of equalization with finite delay.

**TM08-4**

A delta operator approach to discrete-time H-infinity control

Collins, Jr., Emmanuel G.
Florida A&M - Florida State

Song, Tingjun
Florida A&M - Florida State

This paper considers the direct synthesis of discrete-time, H-infinity control laws. The numerical ill-conditioning inherent in using the forward-shift operator at high sample rates is eliminated by representing the discrete-time system and H-infinity controller in the delta domain. The H-infinity design equations for direct synthesis in the delta domain are then developed. This paper also unifies the continuous-time and discrete-time H-infinity design theories by showing that when the sample period Delta=0, the delta-domain H-infinity design equations reduce to the known continuous-time H-infinity design equations.

**TM08-5**

Existence conditions of discrete-time strictly proper H-infinity controllers

Gu, Lei
Southeast Univ.

Feng, Chun-Bo
Southeast Univ.

Xin, Xin
Tokyo Inst. of Tech.

Fei, Shumin
Southeast Univ.

This paper presents sufficient and necessary conditions for discrete-time H-infinity control problems with strictly proper or FDFM controllers based on the LMIs approach. It is shown that there exists a strictly proper or FDFM H-infinity controllers if and only if the standard 3 LMIs condition as well as an additional dynamic one are solvable. The main results are more simple than some previous ones without any additional standard assumptions on the plants.

**TM08-6**

Robust H-infinity control for systems with sector nonlinear uncertainty in actuators

Gu, Yongru
Zhejiang Univ.

Geng, Cheng
Zhejiang Univ.

Qian, Jixin
Zhejiang Univ.

Wang, Leyu
Zhejiang Univ.

This paper focuses on the problem of robust H-infinity feedback control law design for a class of systems with sector nonlinear uncertainty in actuators. The control law can be obtained by solving an algebraic Riccati equation and this avoids the difficulty in solving of Hamilton-Jacobi-Isaac equations.

**TM09-1**

Experimental application of extremum seeking on an axial-flow compressor

Wang, Hsin-Hsiung
Univ. of Maryland

Yeung, Simon
California Inst. of Tech.

Krstic, Miroslav
Univ. of California at San Diego

We show an application of the method of extremum seeking to the problem of maximizing the pressure rise in an axial flow compressor. First we apply extremum seeking to the Moore-Greitzer model and design a feedback scheme actuated through a bleed valve which simultaneously stabilizes rotating stall and surge and steers the system towards the equilibrium with maximal pressure. Then we implement the scheme on a compressor rig in Richard Murray’s laboratory at the California Institute of Technology. We perform stabilization of rotating stall via air injection and implement extremum seeking through a slow bleed valve. The experiment demonstrates that extremum seeking ensures the maximization of the pressure rise starting on either side of the stall inception point. The experiment also resolves a concern that extremum seeking requires the use of periodic probing—the amplitude of probing needed to achieve...
convergence is far below the noise level of the compressor system (even outside rotating stall).

**TM09-2**

**Beneficial actuator-induced bifurcations in compressor control**

Collier, Brian  
Larsen, Michael  
Univ. of Illinois at Chicago  
Univ. of California at Santa Barbara

A controller to stabilize small amplitude fluid oscillations was previously developed. When the controller is used with a slow actuator, performance surprisingly improves. We show that the improvement is due to the inception of a secondary oscillatory instability that competes with the first in a complicated, nonlinear, but favorable manner.

**TM09-3**

**Effects of the shape of compressor characteristics on actuator requirements for rotating stall control**

Wang, Yong  
Murray, Richard M.  
California Inst. of Tech.  
California Inst. of Tech.

We present a systematic analysis on the effects of noise, the shape of compressor characteristics, and bleed valve actuator limits on the performance of controllers in rotating stall control. We use center manifold reduction to the three state Moore Greitzer model with piecewise analytic compressor characteristics. For the reduced system, the optimal control which achieves the largest operability enhancement is the “bang-on” control law that drives the valve to open against its rate limit. For the optimal controller, we also derive approximate formulas for the operability enhancement as a function of the noise level, the actuator limits, and the shape of compressor characteristics. The predictions by the formulas are compared with numerical simulations using a model for a low speed axial compressor.

**TM09-4**

**Robust feedback control of combustion instability**

Hong, Boe-Shong  
Ray, Asok  
Yang, Vigor  
Pennsylvania State Univ.  
Pennsylvania State Univ.  
Pennsylvania State Univ.

This paper presents a robust feedback control system for suppression of combustion instabilities in propulsion systems. The control system is synthesized via the structured singular value technique in the H-infinity setting by taking model uncertainties and exogenous inputs into consideration.

**TM09-5**

**System identification for limit cycling systems: a case study for combustion instabilities**

Murray, Richard M.  
Jacobson, Clas A.  
Casas, R.  
Khibnik, A. I.  
Johnson, C. Richard, Jr.  
Peracchio, A. A.  
Proscia, W. M.  
California Inst. of Tech.  
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Cornell Univ.  
United Technologies Research Ctr.  
United Technologies Research Ctr.

This paper presents a case study in system identification for limit cycling systems. The focus of the paper is on (a) the use of model structure derived from physical considerations and (b) the use of algorithms for the identification of component subsystems of this model structure. The physical process used in this case study is that of a reduced order model for combustion instabilities for lean premixed systems. The identification techniques applied in this paper are the use of linear system identification tools, time delay estimation and qualitative validation of model properties using harmonic balance and describing function methods. The novelty of the paper, apart from its practical application, is that closed loop limit cycle data is used together with a priori process structural knowledge to identify both linear dynamic forward and nonlinear feedback paths.

**TM09-6**

Withdrawn

**TM10-1**

**Fault detection for time-delay systems: a parity space approach**

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LARS-PARIS  
Inst. National Poly. de Lorraine  
Ploix, S.  
LARS-PARIS

In this paper, it is shown how a residual generator can be synthesized for time-delay systems using parity relations. The goal of this study is to investigate the application of a modern symbolic computation like MAPLE to the development and the design of fault detection systems for time-delay systems. In the literature, the problems brought up by time-delay systems has been solved in two different ways at least: retarded functional differential equations based upon the Razumikhin theorem, and the second way is based upon the use of the delay operator z and the properties of the ring R[z]. Taking into account these properties, we propose a FDI scheme based on the parity space. Finally, the applicability of the proposed scheme is illustrated by a numerical example.

**TM10-2**

**A fault detection and diagnosis approach based on hidden Markov chain model**

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Li, Xiao Rong  
Zhou, Kemin  
State Univ. of New York at Binghamton  
Univ. of New Orleans  
Louisiana State Univ.

A fault detection and diagnosis (FDD) approach based on hidden Markov chain model is proposed in this paper. In the proposed approach, the occurrence or recovery of a failure in a dynamic system is modeled as a finite-state Markov or semi-Markov chain with known transition probabilities. For such a hybrid system, either the Interacting Multiple-Model (IMM) or the first-order generalized pseudo-Bayesian (GPB1) estimation algorithm can be used for state estimation, fault detection and diagnosis. The superiority of the approach is illustrated by an aircraft example for sensors and actuators failures. Both deterministic and random fault scenarios are designed and used for evaluating and comparing the performance. Some performance indices are presented. The robustness of the proposed approach to the design of model transition probabilities, fault modeling errors, and the uncertainties of noise statistics are also evaluated.

**TM10-3**

**A decentralized fault detection filter**

Chung, Walter H.  
Speyer, Jason L.  
Univ. of California at Los Angeles  
Univ. of California at Los Angeles

In this paper, we introduce the decentralized fault detection filter which is the structure that results from merging decentralized estimation theory with the game theoretic fault detection filter. A decentralized approach may be the ideal way to health monitor large-scale systems for faults, since it decomposes the problem down into (potentially smaller) “local” problems and then blends the “local” results into a “global” result that describes the health of the entire systems. The benefits of such an approach include added fault tolerance and easy scalability. An example given at the end of the paper demonstrates the use of this filter for a platoon of cars proposed for advanced vehicle control systems.

**TM10-4**

**Multi objective design techniques applied to fault detection and isolation**

Niemann, Henrik  
Stoustrup, Jakob  
Australian National Univ.  
Aalborg Univ.

Various methods for design of fault detectors by using multi objective techniques are presented in this paper. The advantages by using multi objective design methods will be shown. The design methods will be compared to standard fault detection and isolation (FDI) design methods. The FDI problem with uncertain model dynamics is addressed as well.
A multivariable laboratory process with an adjustable zero

Sketching rules for the multivariable root locus design technique

Root-locus-based computational algorithms for control system parameter setting

Bearing and their vibration play an important role in the performance of all motor systems. In many cases, the accuracy of the control is highly dependent on the dynamic performance of the motor bearings. In addition, many problems arising in motor operation are linked to bearing faults. Thus, fault detection of a motor system is inseparably related to the diagnosis of the bearing assembly. This paper presents an approach of using neural networks to detect common bearing defects from motor vibration data. The results show that neural networks can be an effective agent in the detection of various motor bearing faults through the measurement and interpretation of motor bearing vibration signals.

Detection of common motor bearing faults using frequency-domain vibration signals and a neural network based approach

Properties of single input, two output feedback systems

In this paper we describe properties of multivariable feedback control systems for which the plant has a single input and two outputs. Of particular interest are “algebraic” design tradeoffs that occur between different feedback properties at the same frequency. We define concepts of plant and controller direction and alignment, and show that the closed loop response depends upon the alignment between plant and controller. In particular, if alignment is poor, then using high gain will cause output sensitivity to be large and the closed loop system will exhibit large interactions. We also discuss alignment in the case where gain is not necessarily large, and show that alignment isn’t important beyond the closed loop bandwidth. Nor are closed loop properties sensitive to modest amounts of misalignment. Finally, we show there exists a class of controllers that are always poorly aligned with the plant independently of the scaling used for the system outputs.

Parameterization of proper, reduced structure MIMO tracking prefilters with optimality considerations

This paper presents a multivariable extension to [1]. It also presents a method for obtaining optimality in some sense. We consider the problem of continuous tracking of a vector of reference signals, where each signal is assumed to be a linear combination of polynomials, exponentials and sinusoids of known frequencies. The issue is to construct a system such that the performance is optimized, subject to the constraint of zero preview information. As in [1], the concept of orthogonality, is used to construct a prefilter with zero preview information through the solution of a matrix Diophantine equation. This method allows the zero structure of the final sensitivity function to be chosen with great freedom. In addition, we exploit the non-uniqueness of the solution to the matrix Diophantine equation to obtain a prefilter that is optimal in some sense.
In this paper nonlinear trajectory morphing is introduced. This is a way of changing approximate trajectories into true trajectories. We show how it can be used explore the trajectory space of a nonlinear system. A trajectory tracking projection operator is defined for practical implementation of morphing. A pendulum-on-cart example is presented.

Backstepping design for disturbed virtual controls
Shim, H. Seoul National Univ.
Byun, Jijoon Seoul National Univ.
Jo, Nam H. Seoul National Univ.
Seo, Jin H. Seoul National Univ.

In this paper, a class of triangular nonlinear system, having multiplicative time-varying uncertain parameters at each virtual controls, is treated by a backstepping technique. Some motivations for this problem are given, and for that problem, another redesign method after backstepping stabilization is also presented using Artstein-Sontag's theorem.

Controller synthesis for multivariable nonlinear nonminimum-phase processes
Niemiec, Michael Univ. of Michigan
Kravaris, Costas Univ. of Michigan

A general nonlinear controller design method for multivariable nonminimum-phase systems is presented that utilizes a class of synthetic outputs which are statically equivalent to the process outputs. A systematic procedure for the selection of particular synthetic outputs, which lead to prescribed transmission zeros, is outlined. The selected synthetic outputs are then used to construct a model-state feedback controller, which is guaranteed to induce zero steady-state error to the original plant outputs. The proposed control scheme is illustrated in a simulation case study for a multivariable nonisothermal CSTR, where a series/parallel van de Vusse reaction is taking place.

Global and local stability of backstepping adaptive control for time-varying plants
Rabeh, A. Laboratoire d'Automatique
Giri, F. Ecole Mohammadia d'Ingénieurs

The problem of controlling linear plant whose parameters are unknown and time varying is dealt with using a backstepping adaptive controller. The resulting closed loop system is shown to be globally stable for plants with relative degree two. For higher values of the relative degree, the closed loop is locally stable and a bound on the asymptotic performance is established.

Control of nonlinear systems using iterative feedback tuning
Hjalmarsson, Hakan Royal Inst. of Tech.

Iterative Feedback Tuning (IFT) is a tuning method based on minimizing some control criterion directly from experimental data. The method was originally developed for linear time-invariant systems but, rather surprisingly, many successful applications to non-linear system have been reported in the literature. The contribution of this paper is to provide a preliminary analysis of IFT for nonlinear systems. This analysis sheds some light on the question of which nonlinear systems IFT may be expected to work for and also gives some guidance on how to choose the user's design variables for non-linear problems. The discussions are backed up by simulations as well as an application to a DC-servo with backlash which initially exhibits a limit cycle.

Fuzzy modeling and uncertainty-based control for nonlinear systems
Lee, T. S. Georgia Inst. of Tech.

This paper proposes a novel approach to the robust control design for nonlinear dynamical systems based on Takagi and Sugeno's (T-S) fuzzy systems. Only the possible bound of the uncertainty is needed. If the uncertainty is matched, a robust control scheme is proposed, which renders the fuzzy system practically stable. If the uncertainty is mismatched, we show that a mismatched threshold is needed to ensure stability. We apply the control design to a nonlinear missile autopilot problem. The effectiveness of this approach is illustrated by simulation.
Many complex processes having a large number of process variables can be controlled reasonably well by controlling only a small subset of process variables using an equally small number of manipulated variables. This is the central premise of this paper and is referred to as partial control. Knowingly or unknowingly, this idea has been and continues to be applied to successfully control numerous complex industrial processes. Despite its wide-spread use, partial control has never been rigorously defined, presumably because of its rather vague and broad applicability. In this paper, we present a general theoretical framework for defining the partial control problem. Within this framework, we introduce a number of terms such as process variable dominance, modelable responses, practical degrees of freedom and sufficiency of partial control. The framework and the related terminology allow incorporation of a breadth of both engineering-based decisions and more rigorous theoretical tools such as perturbation and sensitivity analysis to achieve the goals of partial control. A number of practical examples illustrate the applicability of these concepts.

**TM13-4 (I) 2108**

*Nonlinear reduced order models for separation processes via augmentation of linear subspace models*

Docter, William A.  
Georgakis, Christos  
Lehigh Univ.  
Lehigh Univ.

This paper presents a general methodology for developing NonLinear Low Order Models (NLLOM) from data collected from large detailed nonlinear models. This methodology is divided into two tasks: development of an Average Linear Low Order Model (ALLOM) and augmentation of the ALLOM with selected nonlinear terms to form the NLLOM. The tools required for the augmentation step that is the focus of this paper include stepwise regression and nonlinear optimization. Results will be presented for the application of these techniques in the development of an NLLOM from a detailed high purity air separation distillation column model supplied by Praxair, Inc.

**TM13-5 (I) 2113**

*Analysis and nonlinear control of an ethyl acetate reactive distillation column*

Vora, Nishith  
Daoutidis, Prodromos  
Univ. of Minnesota  
Univ. of Minnesota

In this work, we study a reactive distillation column for the production of ethyl acetate. Initially we propose a configuration that involves feeding the two reactants in different trays and allows obtaining higher conversion and purity than the conventional configuration that involves feeding in a single tray. A nonlinear controller is then designed to control the product purity in this new configuration with good set-point tracking and disturbance rejection properties, and its performance is compared with that of a linear proportional-integral (PI) controller.

**TM13-6 (I) 2119**

*Experimental comparison of control structures in binary distillation*

Price, Jesse W.  
Sklar, Mikhail  
Univ. of Utah  
Univ. of Utah

**TM14-1 (I) 2118**

*Eliminating non-smooth nonlinearities with compliant manipulator design*

Goldfarb, Michael  
Speich, John E.  
Vanderbilt Univ.  
Vanderbilt Univ.

Compliant mechanism design enables the development of revolute joint-based manipulators without the backlash and Coulomb friction that impede precision position and especially force control. Conventional approaches to compliant mechanism design entail several limitations, however, such as severely limited ranges of motion, poor kinematic behavior, and significant deformation under multi-axis loading. The authors have developed an approach to compliant mechanism design that enables a considerably larger range of motion and significantly better multi-axis revolute joint characteristics than conventional approaches. The approach is based upon the development of a revolute joint that enables the implementation of high bandwidth spatially-loaded revolute joint-based manipulators with well-behaved kinematic characteristics and without the backlash and stick-slip behavior that would otherwise impede precision control. The approach has been incorporated into the design of a small-scale three degree-of-freedom manipulator with an approximately spherical workspace two centimeters in diameter. Though applied to a small-scale manipulator, the design approach is also suited to conventional scale devices. Data from the small-scale manipulator indicates that positioning resolution is limited by digital quantization and sensor noise, and not by more fundamental physical limitations, such as backlash or Coulomb friction.

**TM14-2 (I) 2123**

*On controlling systems with state-variable constraints*

Friedland, Bernard  
New Jersey Inst. of Tech.

State variable constraints may be regions into which the state is forbidden to penetrate or may be physical ("limit stops"). The state-dependent algebraic Riccati equation (SDARE) method can be used to design control systems with constraints of either type. In the former case, a severe penalty function is included in the performance criterion; in the latter case, the physical constraint is modeled by a severely nonlinear spring. Performance is illustrated by an inverted pendulum and the effectiveness of the modeling technique and the SDARE method is demonstrated.

**TM14-3 (I) 2128**

*Friction compensation in the presence of flexibility*

Tao, Gang  
Univ. of Virginia

An adaptive state feedback control scheme is developed for non-canonical form systems with unknown parameters, by employing static state feedback for pole placement and dynamic output feedback for parameter adaptation. The developed control scheme does not need a restrictive state space model matching condition for an adaptive state feedback design. An extended model reference adaptive control scheme is then developed for control of the two-body system with nonlinear friction components in the presence of flexibility.

**TM14-4 (I) 2129**

*Multiresolutional variable structure control of hybrid systems*

Drakunov, Sergey V.  
Meystel, Alexander  
Tulane Univ.  
Drexel Univ.

The paper deals with hierarchical multiresolutional control design for hybrid systems comprised of connected finite automata and continuous system. Control design for hybrid models is treated from a unified point of view by using sliding mode to obtain motion along the desired manifold. The general scheme for the sliding manifold design is based on using the control input from the control on the higher level of hierarchy or/and by using internal hierarchical structure of the particular model. Such models naturally arise in many practical problems such as stabilization and disturbance rejection of systems with discontinuities, hysteresis, backlash etc.

**TM14-5 (I) 2133**

*Robust control of systems involving non-smooth nonlinearities using modified sliding manifolds*

Hatipoglu, Cem  
Ozguner, Umit  
Ohio State Univ.  
Ohio State Univ.

This paper proposes a robust variable structure control design procedure for output reference tracking in continuous-time systems involving input, output and/or state non-smooth nonlinearities. Methods of characterizing such nonlinearities in a standard form are briefly overviewed, analyses methods for stiction and existence of limit cycles are discussed, leading to a design procedure. A design example which involves a discontinuous friction term and an output dead-zone driven by an actuator that has backlash type characteristics is presented.

**TM14-6 (I) 2138**
A variable structure control approach to friction force compensation
Young, K. David YKK Systems

This paper describes a variable structure control approach to the compensation of friction force in two mechanical system control problems. The first one is the active control of sliding base isolator systems which are designed to protect civil structures from excessive ground excitations due to earthquakes. The second one addresses precision positioning, commonly encountered in precision manufacturing and opto-mechanical systems. This approach exploits the well known robustness and disturbance rejection capabilities of sliding mode control to deal with the discontinuity of friction force at zero velocity which is due to Coulomb friction, and with other nonlinear friction characteristics when the relative velocity of the mechanical parts in contact goes through different speed regimes.

TM15-1 2143
Active damping of engine speed oscillations based on learning control
Zaremba, Alexander T. Automated Analysis Corp.
Burkov, I. V. St. Petersburg Tech. Univ.
Stuntz, R. M. Ford Motor Co.

In this paper, we present a learning control scheme for active damping of engine crankshaft oscillations using a supplemental torque source. The scheme comprises a linear feedback controller and learning feedforward term which predicts the engine crankshaft torque. The proposed scheme is computationally efficient and it does not use acceleration signal in the learning procedure.

TM15-2 2148
Control of hybrid-electric vehicles
Lylevshis, Sergey Purdue Univ. at Indianapolis
Yokomoto, Charles Purdue Univ. at Indianapolis

This paper develops nonlinear models for diesel-electric powertrains used in medium- and heavy-duty hybrid-electric vehicles, and describes a new method for designing optimal controllers for highly coupled drivetrains. Current applications of heavy loaded, heavy-duty drives call for the use of comprehensive, innovative ways of handling a large variety of nonlinear phenomena in order to optimize performance and energy conversion, to shape steady-state characteristics, and to meet other desired specifications. This paper demonstrates the application of derived nonlinear models of drivetrain components (diesel, synchronous generator, and traction motor), and an innovative design method is developed to control these highly nonlinear diesel-electric drives.

TM15-3 2150
Feedback control of thermal chlorine (CL2) etching of gallium arsenide (GaAs) using in-situ spectroscopic ellipsometry sensing
Rosen, I. G. Univ. of Southern California
Parent, T. Univ. of Southern California
Chen, P. Univ. of Southern California
Wang, Chunming Univ. of Southern California
Heitz, R. Univ. of Southern California
Nagarajan, M. Univ. of Southern California
Madhukar, A. Univ. of Southern California

Real time feedback control of etching is becoming necessary to meet the degree of process reproducibility demanded by the increasingly strict process requirements of advanced semiconductor manufacturing. The feasibility of using in-situ spectroscopic ellipsometry, being sensitive to film thickness, surface roughness and substrate temperature, to achieve real-time feedback control of etch rate in dry-etching is investigated for the case of thermal chlorine etching of gallium arsenide. The etch rate is modeled as a function of pressure and substrate temperature with all sample preparation and etch rate measurements made in-situ, thus minimizing surface contamination effects. The dynamics of the chamber pressure as controlled by the position of a gate valve in front of a pump is modeled. The resulting nonlinear model with states etch rate, pressure, valve position and valve position velocity, and commanded valve position as control is linearized. A discrete-time Linear Quadratic Gaussian (LQG) compensator is designed and simulated on the nonlinear system.

TM15-4 2155
Draw resonance control for polymer fiber spinning process
Karaman, M. Hutchinson Technology Inc.
Batur, Celal Univ. of Akron

A polymer fiber spinning process is modeled for a draw resonance controller design. We present a second order nonlinear dynamic model which can predict the draw resonance instabilities. Using this model, a nonlinear control system is designed in order to eliminate the draw resonance instabilities at high draw ratios. We present successful simulations of three different control laws based on conventional linearization of nonlinear dynamics, exact linearization technique under some simplifying assumptions, and Lyapunov design technique.

TM15-5 2160
Globally stabilizing controllers for a centrifugal compressor model with spool dynamics
Li, Hua Georgia Inst. of Tech.
Leonessa, Alexander Georgia Inst. of Tech.
Haddad, Wassim M. Georgia Inst. of Tech.

In this paper we develop a globally stabilizing controller for a three-state lumped parameter centrifugal compressor surge model. The proposed model involves pressure and mass flow compression system dynamics as well as spool dynamics to account for the influence of speed transients on the compression surge dynamics. The proposed nonlinear controller architecture involves throttle and compressor torque regulation.

TM15-6 2165
An expert controller for the laminar cooling process of hot rolled slab
Guan, Shouping Northeastern Univ.
Wang, Xiaobo Northeastern Univ.
Chai, Tianyou Northeastern Univ.

A fuzzy logic-based, multi-input/multi-output expert controller has been designed for laminar water curtain controlled cooling system at the Anshan Steel Corporation. This controller can automatically find the specified working points under boundary conditions instead of obtaining them from a lot of experiments. On the basis of these working points, the linearized models can be used to determine the control variables. The simulation results show that the expert controller has an excellent performance and can be used in a practical environment.

TM16-1 (I)
Neural network-based real-time intelligent control of the autoclave cure process
Albin, Jr., Donald C. Lehigh Univ.
Coulter, John P. Lehigh Univ.
Altan, M. Cengiz Univ. of Oklahoma
Li, Xun Univ. of Oklahoma
Rao, Bharath Univ. of Oklahoma

The objective of this work was to demonstrate the use of ultrasonic to determine the end-of-cure for autoclave cured, graphite/epoxy composite laminates. The focus of this paper is to address the installation, and testing of an ultrasonic sensor system developed for a hot press application into an autoclave. The fundamental benefit of this work will be understanding when to alter the process variables in the autoclave and, therefore, consistently produce composite laminates with the desired material properties. An additional benefit
is the potential ability to measure properties of the material directly related to the mechanical performance of the finished component.

**TM16-3 (I) 2170**

**Modeling and control of the in-situ thermoplastic composite tape-laying process**

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In thermoplastic tape-laying, a laminated composite is constructed by local application of heat and pressure. Each new layer is bonded to the previously bonded layers (substrate). The temperature at the interface between the top ply and substrate is critical to achieving interlaminar bonding. Recent research on the in-situ thermoplastic composite tape-laying process has focused on the modeling, numerical analysis and experimental analysis, but little research has considered the control of this process. In this work, a methodology is proposed for modeling and control of in-situ thermoplastic composite tape-laying. The key to the control algorithm is predicting the temperature at the interface between top ply and substrate. Based on a process model, a state feedback controller and a state estimator for temperature are designed for closed-loop control using the linear quadratic method. Two different approaches are used to develop the process model for real-time closed-loop control through temperature feedback. In the first approach, a low order lumped model is constructed from a finite difference scheme. The second approach constructs an empirical model through system identification. The structure of the two models are identical, but the parameters differ. The experimental results have shown a significant improvement in temperature control compared with the previous control method indicating that the proposed modeling and control methodology can produce a high quality thermoplastic composite laminate.

**TM16-4 (I) 3875**

**Development of in-process RTM sensors for thick composite sections**

Rooney, Michael

Biermann, Paul J.

Carkhuff, Bliss G.

Shires, D. R.

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Johns Hopkins Univ.

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Significant and very encouraging results have been obtained on the development and evaluation of sensors for both in-situ pressure measurement and resin progression for thick component resin transfer molding (RTM) processing. Both the pressure and resin progression sensors developed have potential for use beyond its initial target application, experimental validation of 3D flow models using an advantageous resin simulant (Karo® syrup). For pressure measurements, a low-cost, commercially-available pressure sensor has been identified, modified and successfully tested while immersed in the resin simulant. However, no commercially-available alternative for resin progression monitoring was located that would meet desired continual flow resolution requirements. To meet this challenge, an innovative concept for a capacitive sensor has successfully progressed through feasibility studies and well into prototype design, demonstration and sensitivity evaluation.

**TM16-5 (I) 2176**

**Optimization of gate and vent locations for resin infusion processes using genetic algorithms**

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Advani, Suresh G.

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U.S. Army Research Lab

In composite manufacturing processes, such as RTM and VARTM, resin is infused into a mold containing a preform. The location where the resin is injected is called a gate and the location through which the air is extracted is called a vent. The Liquid Injection Molding Simulation (LIMS), which was developed at the University of Delaware, is capable of simulating the movement of the resin flow fronts through a fiber preform, when the gate and vent locations are specified. When two flow fronts meet and trap air between them, a resin-starved area, called a ‘dry spot’, is formed, causing a structural weakness in the final composite part. This problem can be solved by the optimal placement of gates and vents. In order to determine optimal gate and vent locations, a genetic algorithm has been used here as a search tool. The objective function for the optimization is expressed as a Process Performance Index and incorporates the fill time and dry spot formation. The PPI is at a minimum at the optimum gate and vent(s) configuration. We demonstrate the method through a case study, where less than 1% of the possible LIMS simulations were required to find a near-global optimum.

**TM16-6 (I) 2181**

**Real-time sensing and control of resin flow in liquid injection molding processes**

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This paper presents results from an experimental investigation into real-time sensing and control of resin flow in an RTM process. The objective of the research was to develop intelligent process control methodologies using in-situ sensors and process models, for real-time control of the RTM process. Real-time control of the RTM process will enable an increase in throughput, high yields, low defects, and consistent repeatability of quality between the parts. We concentrated on controlling the resin flow using multiple injection ports and vent locations. The results from the preliminary investigations indicate the feasibility of implementing real-time control on the RTM production floor.

**TM17-1 (I) 2185**

**Advanced control techniques for robotic manipulators**

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In this tutorial, dynamic models of rigid body robots (RBRs), robots having motor dynamics (RMDs) and flexible joint robots (FJRs), are firstly presented in the order of complexity. Controller design is then formulated in a unified fashion for these three kinds of robots because of their inherent similar physical and mathematical properties. After a brief review of basic control techniques being used, controller design for RBRs is discussed in detail and a comprehensive list of passive parameter estimators and robust parameter estimators is given. Subsequently, the control problems for RMDs and FJRs are treated in turns. While the two systems are different, it can be seen that they have very much similar properties, and accordingly can be analyzed similarly. It is shown that most of the existing popular controllers are special cases of the unified framework presented and derivations and proofs can be simplified owing to the common background of the problems.

**TM17-2 (I) 2200**

**Critical implementation issues in compensation for nonlinearities in industrial robot manipulators by adaptive multilayer neural networks**

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Lee, T. H.

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National Univ. of Singapore

To improve the performance of an industrial robot manipulator with linear individual-joint controllers, an adaptive feedforward Multilayer Neural Network (MNN) is proposed as an addition to the existing linear control structure at each joint to compensate the nonlinearity. System stability is guaranteed by three measures: the initialization of the MNN, which ensures that the MNN’s learning start from a reasonable point; a Lyapunov-based adaptive law, in which the MNN is linearized and the residual error is tolerated by a dead-zone or a leakage term; and a contribution function, which manipulates the contribution of the MNN to the system. The MNN and the control algorithm are implemented on a TMS320C30 digital signal processor. The realization on a two-link manipulator demonstrates the effectiveness of the proposed scheme.
This paper summarizes recent advancements on the adaptive robust control (ARC) of robot manipulators. Some of the critical implementation issues are discussed. These issues include (i) the selection of suitable ARC controller structures for reducing on-line computation time and the effect of noisy velocity measurement, (ii) on-line desired trajectory generation and initialization for a better transient performance, (iii) the tuning of controller parameters in implementation for achieving high performance, and (iv) the selection of the bounds of physical parameters and controller parameters to alleviate the effect of control saturation. Comparative experimental studies done on a SCARA type direct-drive robot are presented to illustrate the advantages and the drawbacks of qualitatively different adaptive and robust control algorithms.

Robust controller design and implementation for industrial robots: electrically driven rigid body robots

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Su, Chun-Yi
Univ. of Victoria
Tang, S.
International Submarine Eng. Ltd.

In this paper the issue of robust controller design and implementation for rigid-link electrically-driven robot manipulators was addressed. The main features of this scheme eliminate the requirement of the joint velocity measurements and the boundedness of estimated inertia parameters of the manipulator. To illustrate the feasibility of this controller, it was implemented on a Reis V15 industrial manipulator. The effectiveness of the proposed control strategies has been confirmed by experiments.

Further experimental results on nonlinear control of flexible joint manipulators

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Laboratoire d’Automatique de Grenoble

In this note we focus on the experimental comparison of feedback controllers for flexible joint manipulators. It compares a previous set of experimental results on a 2 degree-of-freedom ( dof) manipulator with a stiff second joint (50 Nm/rad). The process considered here is quite different since it consists of a 1 dof flexible joint manipulator (i.e. a 4th order linear system) with a high flexibility (3.4 Nm/rad). The main goal of the present work is to apply a systematic way of tuning the gains of backstepping- and energy shaping-like controllers, using a method developed for LQ controllers by De Larminat. Notice that although other linear controllers could be applied to the process tested in this note, we restrict ourselves to those control laws that extend to the nonlinear general case of flexible joint manipulators, and yield global stability results.

Global stabilization of uncertain mechanical systems with bounded controls

Barany, Ernest
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Colbaugh, Richard
New Mexico State Univ.

This paper considers the problem of globally stabilizing a mechanical system with unknown potential and inertial structure and without the need for velocity measurements or large forces. We first consider two large classes of dynamical controllers and show that in a sense the goals of stabilization without system details and without velocity measurement is incompatible with the requirement of global stabilization without large forces. To solve this problem we turn to a hybrid strategy where we combine an effective stabilization strategy using bounded controls with a semiglobal large force PID-type controller.

Adaptive variable bias magnetic bearing control

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Brown, Gerald V.
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Virginia Tech.

Most magnetic bearing control schemes use a bias current with a superimposed control current to linearize the relationship between the control current and the force it delivers. With the existence of the bias current, even in no load conditions, there is always some power consumption. In aerospace applications, power consumption becomes an important concern. In response to this concern, an alternative magnetic bearing control method, called Adaptive Variable Bias Control (AVBC), has been developed and its performance examined. The AVBC operates primarily as a proportional-derivative controller with a relatively slow, bias current dependent, time-varying gain. The AVBC is shown to reduce electrical power loss, be nominally stable, and provide control performance similar to conventional bias control. Analytical, computer simulation, and experimental results are presented in this paper.

Limitation of linear controllers for precision magnetic bearings with uncertainties

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In order to investigate the achievable performance robustness of the control system for magnetic bearings used for precise positioning, an input-output linearization is applied to an existing system. With structured singular value plots, the limitation of linear controllers for the magnetic bearing with unknown rotor mass is evaluated. The increase in controller gain when the system is close to its performance limit is revealed. The achievable robustness with bandwidth limit is also evaluated to achieve stability robustness for the system with high-frequency unmodeled dynamics.

Speed regulation of an induction motor using methods from nonholonomic control

Pettersen, Kristin Y.
Norwegian Univ. of Science & Tech.
Egeland, Olav
Norwegian Univ. of Science & Tech.

The paper shows how methods developed for control of nonholonomic vehicles can be used to derive a feedback control law for speed and flux regulation of an induction motor. The resulting control law yields stability and exponential convergence to the speed and flux reference. The flux amplitude takes values depending on the speed error, as opposed to taking a nonzero prescribed value. The control law is continuous and has no singularities, it does not cancel any dynamics, and the exponential stability provided by the control law is robust to model parameter uncertainty. Simulation results are presented.

Design and implementation of a robust controller for a free gyro-stabilized mirror system

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Chen, Ben M.
National Univ. of Singapore
Lee, Tong-Heng
National Univ. of Singapore

In this paper, we consider the problem of designing a robust controller for a multivariable servomechanism of a free gyro-stabilized mirror system where there exists cross coupling between the axes. The overall design has been implemented using a personal computer with C++ and tested on the actual gyro-stabilized mirror system. Our simulation and implementation results show that the design is very successful.

A digital H-infinity loop shaping controller for an active mass driver system: a benchmark problem in controlling buildings

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Bahrain Telecom Co.
A direct robust digital design for a benchmark problem in controlling buildings will be presented. The structure considered is a scale model of a three (3) story building employing an active mass driver. A simulation program has been developed and made available to test the efficiency and merit of the design method which will be based on discrete-time loop shaping with robust stabilization via H-inf optimization. The emphasis in the design will be to obtain a reasonably low-order controller, synthesized without resorting to complex loop shaping filters.

**TP02-1 (I) 2243**  
*Nonlinear damping in vehicle lateral control: theory and experiment*  
Chen, Chieh, Applied Komatsu Technology  
Guldner, Jurgen, BMW Technik GmbH  
Kanelilakopoulos, Ioannis, Univ. of California at Los Angeles  
Tomizuka, Masayoshi, Univ. of California at Berkeley

The sensor and actuator limits in real-world control systems imposes unavoidable tradeoffs between performance and the size of the operating region. When linear control design techniques are used, these limits are either neglected or accounted for by lowering the gains of the controller. The former results in severe reductions of the operating region, while the latter yields low performance. These tradeoffs can often be mitigated by using a nonlinear control strategy, in which nonlinear terms are intentionally introduced in order to implement different design objectives in different operating regions. In this paper, nonlinear damping is utilized as a design tool in lateral control of automated vehicles. Design considerations of the vehicle lateral controller include lateral tracking errors, passenger ride quality and reference/sensing system characteristics. It is shown that the intentionally introduced nonlinear damping term in the feedback loop possesses several favorable design features in the lateral control system. Experimental results using a full scale automated vehicle show that passenger comfort can be enhanced for small errors by significantly reducing the original controller gains, while at the same time achieving the same level of maximum lateral tracking errors.

**TP02-2 (I) 2248**  
*Automatic steering control of vehicle lateral motion with the effect of roll dynamics*  
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Tan, Han-Shue, Univ. of California at Berkeley  
Tomizuka, Masayoshi, Univ. of California at Berkeley

The two dominant motions of automatic vehicle steering control are yaw and lateral motion. A two degree-of-freedom (DOF) model commonly used to describe these motions is called the bicycle model. Experimental results for certain vehicles, however, show the lowered gain characteristics in the lateral acceleration response to the steering input. This is attributed to suspension dynamics. In this paper, a 3 DOF linear model, which incorporate the suspension roll mode, is developed and verified against the experimental data. The H-infinity theory is applied to the bicycle model and the 3 DOF model for synthesis of robust steering controllers. The simulation results indicate the importance of the effect of roll dynamics to steering controller design.

**TP02-3 (I) 2253**  
*Nonsmooth estimation and adaptive control with application to automotive brake torque*  
Maciuca, Dragos B., Univ. of California at Berkeley  
Hedrick, J. Karl, Univ. of California at Berkeley

Estimation and adaptive control has been successfully used when system parameters are unknown or slowly time varying. One requirement of such algorithms is that, in order for the parameters to converge, the signal must be “persistently excited”. When the signal is not rich enough to meet this requirement, it is intuitively possible to self excite it by using a switching control input. In this paper, a formal analysis of such a method is performed. Its application to the estimation and adaptive control of automotive brake torque is also presented. Experimental results are used to corroborate the theory developed.

**TP03-1 2257**  
*Model-based multivariable fuzzy adaptive controller for paper-making process*  
Zheng, Huailin, Southeast Univ.  
Chen, Weinan, Southeast Univ.

Through modifying the CPN model, a kind of multivariable fuzzy model is put forward, then the matching fuzzy multistep prediction control algorithm is deduced based on the model. The modified model works in a competitive output manner which results in its local representation property. While studying on-line, only a few parameters need to be regulated. So the model has the merits of fast learning and on-line self-organizing modeling. The control algorithm based on the model is simple, adaptive and useful in multivariable and time delay systems. While the algorithm is used in paper-making system, simulations show its good effect.

**TP03-2 2274**  
*Design of fuzzy direct adaptive controller and stability analysis for a class of nonlinear systems*  
Piao, Ying-Guo, Northeastern Univ.  
Zhang, Hua-Guang, Northeastern Univ.  
A direct adaptive tracking control architecture based on fuzzy logic is developed for a class of nonlinear dynamic system. In the procedure, the controller is composed of fuzzy approximate controller and fuzzy sliding mode compensating controller. Global asymptotic stability of the algorithm is established in the Lyapunov sense, with tracking errors convergence to a neighborhood of zero. Simulation results demonstrate the effectiveness of the proposed algorithm.

TP03-3  2276
A multivariable fuzzy generalized predictive control approach and its performance analysis  
Zhang, Hua-Guang  Korea Adv. Inst. of Science & Tech.  

In this paper, we use T-S fuzzy model to express nonlinear dynamic systems, and present a new fast on-line identification algorithm about its parameters. A multivariable fuzzy generalized predictive control approach is put forward based on the identified fuzzy model by means of Clark's principle of single-variable generalized predictive control. The steady state performance and stability of the closed-loop system are analyzed in detail too.

TP03-4  2281
Failure-tolerant control of aircraft: a fuzzy logic approach  
Schram, G.  Delft Univ. of Tech.  
Copina, G. J. C.  Delft Univ. of Tech.  
Brujin, P. M.  Delft Univ. of Tech.  
Verbruggen, H. B.  Delft Univ. of Tech.

A new approach to failure-tolerant control is introduced by using multiple fuzzy controllers in an adaptive control scheme. Each fuzzy controller corresponds to a particular failure type. In contrast to the multivariable fuzzy generalized predictive control approach, smooth transitions and a gradual interpolation between the failure control modes is achieved by using fuzzy logic. Moreover, in contrast to gain-scheduling approaches, control modes with different structure can still be defined. The approach is demonstrated on a nonlinear, six degrees of freedom model of a transport aircraft under realistic assumptions about actuator dynamics. The results show that good performance is achieved in case of severe actuator failures.

TP03-5  2286
Recursive optimization procedure for fuzzy-logic controller synthesis  
Taylor, James H.  Univ. of New Brunswick  
Sheng, Lan  Univ. of New Brunswick

We present a new method for the synthesis of fuzzy-logic controllers (FLCs) for amplitude-sensitive nonlinear plants based on sinusoidal-input describing-function (SIDF) methods plus step-response optimization. This method involves a two-step process wherein an initial controller is obtained via the direct generation of the membership functions and output levels based on the “frequency response” of the nonlinear plant in the describing-function sense, then the FLC is perfected via recursive optimization of the step responses for a specified set of input amplitudes. By “recursive” we mean that the average step-response obtained from step k is used as the objective for the k+1 optimization problem, and the process iterates until convergence, with the objective of achieving closed-loop system performance that is as insensitive to reference-input amplitude as possible for the selected controller configuration. An illustration of the method and its effectiveness is provided, based on a prototypical position control problem where a servo motor plus mechanical load are characterized by torque saturation and nonlinear friction (stiction). This approach is capable of treating nonlinear systems of a very general nature, with no restrictions as to system order, number of nonlinearities, configuration, or nonlinearity type.

TP03-6  2289
Fuzzy damage-mitigating control of a fossil-fueled power plant  
Holmes, Michael Scott  Pennsylvania State Univ.  
Ray, Asok  Pennsylvania State Univ.

This paper presents the architecture and synthesis of a damage-mitigating control system where the objective is to achieve high performance with increased reliability, availability, component durability, and maintainability. The proposed control system has a two-tier structure. In the lower tier, a linear sampled-data controller tracks a reference trajectory vector while the upper tier contains a fuzzy-logic-based damage controller which makes a trade-off between system dynamic performance and structural damage in critical component(s). The synthesis procedure is demonstrated on the model of a commercial-scale fossil-fueled power plant. Simulation results are presented which demonstrate the trade-off between plant dynamic performance and structural damage in a critical component.

TP04-1  2294
A new analysis technique without frequency gridding  
Ferreris, Gilles  CERT-ONERA  
Biannic, Jean-Marc  CERT-ONERA

The aim of this paper is to directly compute an upper bound of the maximal structured singular value over a frequency interval. In the context of the mixed mu upper bound of Fan, Tits and Doyle, heuristic methods have been proposed namely to synthesize D, G scaling matrices, which simultaneously work at two neighboring frequencies. Interestingly, even if the latter are not a priori very close, it remains possible to synthesize D, G scaling matrices, which simultaneously work at those two frequencies and to check a posteriori that D and G work indeed on the whole segment. An important contribution of this paper is to provide an easy and yet rigorous method, for solving this last problem. The technique is finally successfully applied to a non academic example, which may be significant of a large flexible system.

TP04-2  2299
A new perspective on computing robust stability margins for complex parametric uncertainties  
Basker, V. R.  Univ. of Florida  
Latchman, Hanip A.  Univ. of Florida  
Mahon, H. Michael  Univ. of Florida  
Crisalle, Oscar D.  Univ. of Florida

A new and simple approach to the problem of finding robust stability margins for SISO systems with complex parametric uncertainties is proposed. The technique is based on the recently developed critical direction theory, and is an alternative to existing methods such as those based structured singular value formulations. The uncertainties considered belong to highly structured domains satisfying a radial convexity condition. Explicit and exact stability conditions are derived using intuitive geometric arguments. The approach recovers previous results given in the literature for the special case of disk-bounded affine complex uncertainties. Examples are given for rectangular and elliptical uncertainty domains.

TP04-3  2301
A new method for computing robustness margins for real parametric uncertainties  
Mahon, H. Michael  Univ. of Florida  
Crisalle, Oscar D.  Univ. of Florida  
Latchman, Hanip A.  Univ. of Florida  
Yen, K. H.  Univ. of Florida

A new method is proposed for computing the robust stability margin for a single-input single-output systems subject to real interval uncertainties that appear multiaffinely in the system transfer function. The approach utilizes the recently developed critical direction theory to study the robust stability problem directly in the Nyquist plane, and permits the calculation of the robust stability margin using a bisection search. A further benefit of the method is that a reduced range of frequencies yielding the robustness margin can be readily identified. An algorithm is presented which utilizes both of these properties, resulting in a significant reduction in computational burden.

TP04-4  2304
An algorithm of symbolic computation for stability margin

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**Authors:**

- Biannic, Jean-Marc
- Ferreres, Gilles
- Holmes, Michael Scott
- Latchman, Hanip A.
- Mahon, H. Michael
- Crisalle, Oscar D.
- Yen, K. H.
- Zhang, Hua-Guang
- Bien, Zeungnam
- Schram, G.
- Copina, G. J. C.
- Brujin, P. M.
- Verbruggen, H. B.
- Taylor, James H.
- Sheng, Lan
- Holmes, Michael Scott
- Ray, Asok
- Mahon, H. Michael
- Crisalle, Oscar D.
- Latchman, Hanip A.
- Yen, K. H.
- Biannic, Jean-Marc
- Ferreres, Gilles
This paper introduces a new algorithm to solve a stability robustness problem by using differential topological concepts based on symbolic computation. Despite the well-known results shown that the real robustness margin problem is NP hard, this paper has shown that we can achieve the accurate robustness margin of the grid method without suffering the troublesome complexity of the grid method.

TP04-5

A necessary and sufficient 'virtual (interior) edge' solution for checking robust stability of interval matrices

Yedavalli, Rama K.
Ohio State Univ.

This paper addresses a current research topic of high interest, namely the issue of developing a finitely computable necessary and sufficient test for checking the robust stability of an interval matrix and provides a complete solution to the problem in the form of an 'edge' (a one dimensional search) result. The result uses the fact that the robust stability problem can be converted to a robust nonsingularity problem involving the original matrix and the associated bialternate sum matrix (which we label as the 'tilde' matrix). The special nature of the 'tilde' matrix is exploited with the introduction of a concept labeled 'real axis nonsingularity.' In addition, another new concept called 'Virtual Matrix Family' is introduced which indirectly captures the 'interior' of the uncertain matrix family. Using a measure labeled 'Weighted Real Axis Determinant,' which is positive for an asymptotically stable matrix, the proposed necessary and sufficient condition involves checking if the Weighted Real Axis Determinant of the 'virtual edge' matrices are greater than the minimum of the Weighted Real Axis Determinants of the vertex matrices. This condition is to be checked in the 'tilde' matrix space. The proposed methodology is illustrated with a variety of examples. The importance of this result in the context of available results in uncertain polynomial theory and the scope of this result is discussed.

TP04-6

Spherical mu
Khatri, Sven Hiralal
Parrilo, Pablo A.
California Inst. of Tech.
California Inst. of Tech.

A generalization of the structured singular value, mu, with spherical constraints on the uncertainty is presented. A linear matrix inequality (LMI) upper bound, which is analogous to the standard mu LMI upper bound, is derived. The consistency of these bounds with each other is validated. Another upper bound to the same problem using the implicit formulation is presented.

TP05-1

Do all linear flexible structures have convergent second-order observers?
Balas, Mark J.
Univ. of Colorado at Boulder

Yes, but they are not natural.

TP05-2

Multi-rate nonlinear state and parameter estimation in a bioreactor
Tatiraju, Srinivas
Soroush, Masoud
Mutharasan, Raj
Drexel Univ.
Drexel Univ.
Drexel Univ.

This paper concerns real-time, multi-rate, nonlinear, state and parameter estimation in a pilot-scale, mouse-mouse hybridoma cell, biochemical reactor. A multi-rate estimator is designed and implemented to estimate specific growth rate and concentrations of viable cells, total cells, glucose, glutamine, and monoclonal antibodies (MAb) in the reactor. These are estimated from frequent measurement (inferred values) of oxygen uptake rate (OUR) and infrequent and delayed measurements of the concentrations of viable cells, total cells, glucose, glutamine, and MAb. The infrequent measurements are available every 2 to 17 hours with time delays of 0.08 to 2.00 hours, and OUR is inferred from dissolved oxygen concentration measurements that are available every 0.17 hour.
affecting the system are zero-mean stationary whereas the closed-loop system operates under an external (possibly noisy) cyclostationary input. The closed-loop system must be stable but it is allowed to be unstable in open-loop. Recently various techniques have been proposed for system identification using cyclic spectral analysis. Having obtained a model, how do we know if the fitted model is “good”? This paper is devoted to the problem of model validation using cyclic spectral analysis. We propose a simple statistical test based upon the estimated cyclic spectrum of an output error signal. Model order estimation is a by-product of the model validation procedure. Computer simulation examples are presented in support of the proposed approaches.

TP06-3 2359
SM evaluation of frequency response variation rate for H-infinity identification
Giarre, Laura Politecnico di Torino

Set membership (SM) H-infinity identification for discrete time systems is aimed to estimate a low order approximating model and its identification error. A choice of the gridding in frequency is presented, based on a set-membership estimation of the rate of variation of the system frequency response.

TP06-4 2361
Model set validation and update for time-varying SISO systems
Nagamune, Ryozo Royal Inst. of Tech.
Yamamoto, Shigeru Osaka Univ.

This paper presents a method of the model set validation and update for time-varying SISO systems by using time-domain data. As a representation of such systems, we use a discrete-time linear difference equation with time-varying parametric uncertainties measured by the weighted infinity norm. It is shown that the validation can be simply conducted by comparisons of distances in a parameter space, and that the update is done by solving a convex optimization problem in general, and by giving an explicit solution in a special case. Based on these results, we propose an off- and online algorithm of the model set validation and update, respectively.

TP06-5 2366
Nonlinear identification of control systems
Lychevski, Sergey Purdue Univ. at Indianapolis

Nonlinear system identification of dynamic systems is a topic of growing interest. The ability of model-based systems analysis and design to attain the desired objectives depends to a large degree on the accuracy of the mathematical models derived and parameters used. To avoid deficiencies associated with model validation and order estimation, accurate mathematical models should be found by using the fundamental laws, and the unknown parameters have to be identified to perform analysis, design, and prototyping. This paper thoroughly studies the model-relevant identification concept for continuous-time nonlinear multi-input/multi-output systems in time-domain by using a nonlinear mapping-based identification framework. Discrete-time and hybrid systems play an important role due to microprocessor-, microcomputer-, and DSP-based hardware platforms applied to implement comprehensive control algorithms in order to attain the desired objectives, specifications, and capabilities. However, the majority of systems to be controlled are continuous-time, and analog control is a manageable and straightforward solution in many practical problems. The importance of the researched time-domain concept lies on the need to identify continuous-time systems to be used in the corresponding analysis, design, stabilization, and optimization. As an illustrative example, the unknown parameters of a high-performance aircraft are identified using the flight data.

TP06-6 2371
Nonlinear system identification using genetic algorithms with application to feedforward control design
Luh, Guan-Chun Tatung Inst. of Tech.
Rizzoni, Giorgio Ohio State Univ.

A GAMAS-based system identification scheme is developed to construct NARX model of nonlinear systems. Several simulated examples demonstrate that it can be applied to identify both nonlinear continuous-time systems and discrete-time systems with acceptable accuracy. Inverting the identified NARX model, a feedforward controller may be derived to track desired time varying signal of nonlinear systems. Sufficient conditions of the invertibility of NARX model are proposed to investigate the existence of the inverse model. Simulation results depict the effectiveness of the feedforward controller with the aid of simple feedback controller designed for regulation purpose.

TP07-1 2376
On rate-based congestion control in high speed networks: design of an H-infinity based flow controller for single bottleneck
Ozbay, Hitay Ohio State Univ.
Kalyanaraman, Shivkumar Rensselaer Polytechnic Inst.
Iftar, Altug Anadolu Univ.

Typical congestion control algorithms for high speed networks include local flow controllers at the bottleneck nodes. In this paper an H-infinity based controller is developed for rate feedback in a single bottleneck network. The rates can be assigned to the sources only after a certain transmission delay. Controller design specifications for this time delay system include “fairness” to multiple users, “usage” optimization, and minimization of the transients in the queue length. Stability robustness against uncertainties in time delays is also considered. By a simple algebra the problem is transformed to an H-infinity control of a plant with a time delay, and it is solved by using an algorithm developed earlier for this class of problems.

TP07-2 2381
Stabilization of linear systems with simultaneous state, actuation, and measurement delays
Kapila, Vikram Polytechnic Univ.
Haddad, Wassim M. Georgia Inst. of Tech.
Grivas, Apostolos Polytechnic Univ.

This paper considers the problem of stabilizing continuous-time linear systems with time delays. Specifically, a fixed-order (i.e., full- and reduced-order) dynamic compensation problem is addressed for systems with simultaneous state, input, and output delays. The principal result involves sufficient conditions for characterizing fixed-order dynamic controllers for delay systems via a system of modified coupled Riccati equations. The controllers obtained are delay independent and hence apply to systems with arbitrary unknown delay.

TP07-3 2386
Some topics in real-time control
Nilsson, Johan Lund Inst. of Tech.
Bernhardsson, Bo M. Lund Inst. of Tech.
Wittenmark, Bjorn Lund Inst. of Tech.

This paper discusses three problems that can arise in distributed real-time control systems. First the LQG-control problem is solved for the case with both varying transmission delays and sampling interval jitter. The second problem investigated is if control performance can be increased by using timeouts in a system with varying transmission delays. An ad hoc controller that can increase control performance is presented. The third problem studied is the structure of the varying delays arising due to use of asynchronous loops in control systems.

TP07-4 2391
A unified approach to time-delay system control: robust and gain-scheduled
Scorletti, Gerard ENSTA
Fromion, Vincent Univ. di Roma

This paper considers the output-feedback performance control of a large class of uncertain linear time-delay systems, that is, systems where (time varying) dynamical and parameter uncertainties are explicitly modeled. For a controller with a given structure, we propose design methods based on both time-delay independent and
time-delay dependent conditions. Depending on the selected controller structure, these conditions are convex or not. In the first case, the conditions can be cast as an optimization problem involving Linear Matrix Inequalities (LMI) and in the second case, an heuristic approach based on LMI optimization is presented. All the conditions are directly derived from a general result. In contrast with most time-delay control methods, our result are developed in an input-output framework. Our conditions recover and generalize previous ones.

TP07-5 2396
Fixed-structure controller synthesis for systems with input nonlinearities and time delay
Kapila, Vikram Polytechnic Univ.
Haddad, Wassim M. Georgia Inst. of Tech.
Grivas, Apostolos Polytechnic Univ.

In this paper we consider the problem of stabilizing continuous-time linear systems containing input nonlinearities and time delays. Specifically, a fixed-order (i.e., full- and reduced-order) dynamic output feedback control technique is proposed and sufficient conditions involving a closed-loop modified Riccati equation is presented for stabilization of systems with sector bounded input nonlinearities and state and measurement time delays.

TP07-6 2398
An LMI approach to H-infinity control for linear delay systems
Jeong, Eun Tae Changwon National Univ.
Kwon, Sung-Ha Changwon National Univ.
Kim, Jong Hae Kyungpook National Univ.
Park, Hong Bae Kyungpook National Univ.

This paper presents an H-infinity controller design method for linear systems with delayed states, inputs, and measurement outputs. Using a Lyapunov functional, the stability for delay systems is discussed independently of time delays. And a sufficient condition for the existence of H-infinity controllers of any order is given in terms of three linear matrix inequalities (LMIs). Based on the positive definite solutions of their LMIs, we briefly explain how to construct H-infinity controller, which stabilizes time delay systems independently of delays and guarantees an H-infinity norm bound.

TP08-1 2403
Parametric robust H-infinity controller synthesis: comparison and convergence analysis
Banjerdpongchais, David Chulalongkorn Univ.
How, Jonathan P. Stanford Univ.

Recent papers have demonstrated the effectiveness of our iterative algorithm using linear matrix inequalities (LMIs) on several parametric robust H-infinity control designs. This paper presents two additional important components to the discussion on the behavior of the new LMI-based iterative algorithm: a comparison study between the LMI synthesis technique and the existing iterative approaches of the complex and mixed mu/Km synthesis, and a convergence analysis of this new algorithm. The results indicate that the Popov H-infinity controller synthesis provides a viable alternative for designing real parametric robust controllers and exhibits properties similar to the D-K and D,G-K iteration of the complex and mixed mu/Km synthesis. The key potential advantage of using the LMI approach is the elimination of the curve-fitting for the D and G scaling functions.

TP08-2 2405
Robust H-infinity reliable control for linear state delayed systems with parameter uncertainty
Wang, Zidong Ruhr-Univ. of Bochum

This paper focuses on the problem of robust H-infinity reliable control design for linear systems with state delay and parameter uncertainty. The goal of this problem is to design the state feedback controller such that, for all admissible uncertainties as well as actuator failures, the plant is robustly stabilized and the prescribed H-infinity-norm bound constraint on disturbance attenuation is guaranteed, simultaneously. It is assumed that, the parameter uncertainties are norm-bounded and the actuator failures occur among a prespecified subset of actuators. A simple, effective, modified algebraic Riccati equation approach is developed to solve the addressed problem. The resulting time-delay control systems are reliable in that they provide guaranteed robust stability and H-infinity performance not only when all control components are operational, but also in case of actuator failures. An illustrative example is presented to demonstrate the applicability of the proposed method.

TP08-3 2410
Robust H-infinity controller design for linear time-varying uncertain systems with delayed state and control
Wang, Jingcheng Zhejiang Univ.
Su, Hongye Zhejiang Univ.
Chu, Jian Zhejiang Univ.
Yu, Li Zhejiang Univ.

This paper focuses on analysis and synthesis of robust control for linear time-varying uncertain dynamic systems with delayed state and control. A static state feedback controller is presented to quadratically stabilize the uncertain system and reduce the effect of the disturbance input on the controlled output to a prescribed levels for all admissible uncertainties. Sufficient conditions in the form of ARI for robust control are derived. Two methods are given for robust controller synthesis. One is to construct the robust controller by an equivalent linear time-invariant structural description for the sufficient conditions. The other method is to transform the sufficient conditions into an LMI problem and thus no tuning of the parameters is needed to obtain a robust controller.

TP08-4 2415
Robust reliable H-infinity control for uncertain time-delay systems
Gu, Yongru Zhejiang Univ.
Geng, Cheng Zhejiang Univ.
Qian, Jixin Zhejiang Univ.
Wang, Leyu Zhejiang Univ.

This paper focuses on the problem of robust reliable H-infinity control design for linear systems with delayed state and with norm-bounded parameter uncertainty in the state matrix. The resulting control systems are reliable in that they provide guaranteed stability and H-infinity performance for all possible actuator failures within a prespecified subset of actuators as well as all admissible uncertainties.

TP08-5 2417
Robust H-infinity control for linear time-delay systems subject to norm-bounded nonlinear uncertainty
Gu, Yongru Zhejiang Univ.
Geng, Cheng Zhejiang Univ.
Qian, Jixin Zhejiang Univ.
Wang, Leyu Zhejiang Univ.

This paper focuses on the problem of robust H-infinity control for linear uncertain time-delay systems with norm-bounded nonlinear uncertainty in both the state and control. Also, the time delay is time-varying and can exist both in the state and control. Using the fact that the type of nonlinear uncertainty set considered here has an equivalent representation by linear uncertainty set, we propose an approach for designing a memoryless state feedback control law which will stabilize the time-delay systems and, simultaneously, guarantee a prespecified H-infinity disturbance attenuation constraint for all admissible uncertainty.

TP08-6 2421
Robust H2 control of descriptor system with time-varying uncertainty
Takaba, Kiyotsugu Kyoto Univ.
Katayama, Tohru Kyoto Univ.

This paper considers the robust H2 control problem for a descriptor system with time-varying structured uncertainty. We first derive a computational formula of the H2 norm for a time-varying descriptor system using a generalized Lyapunov differential equation. Then, a sufficient condition for the robust H2 performance is given in terms of
a linear matrix inequality (LMI). Based on this LMI condition, we develop a design method of a descriptor variable feedback controller achieving the robust performance. The present design method can solve the robust H2 control problem for a wider class of plants than the state-space approach.

**TP09-1**

Multiple target tracking using a multirate IMMJPDA algorithm  
Hong, Lang  
Ding, Zhen  
Wright State Univ.  
Wright State Univ.

A multirate interacting multiple model joint probabilistic data association (MRIMMJPDA) tracking algorithm is developed in this paper. The MRIMMJPDA combines two powerful algorithms, the multirate interacting multiple model (MRIMM) tracking algorithm and the joint probabilistic data association (JPDA) algorithm, such that both maneuvering and nonmaneuvering targets in clutters can be tracked effectively and efficiently.

**TP09-2**

The PMHT for maneuvering targets  
Ruan, Yanhua  
Willett, Peter K.  
Streit, Roy  
Univ. of Connecticut  
Univ. of Connecticut  
Naval Undersea Warfare Ctr.

Via the EM algorithm and a slight modification of the usual target-tracking assumptions, the Probabilistic Multi-Hypothesis Tracker (PMHT) of Streit and Luginbuhl combines data-association and filtering to a simple, elegant, and efficient iterative procedure. The PMHT works well; but part of its appeal is a consistent and extensible statistical foundation. Here we show one such extension, that designed to track maneuvering targets. The basis, as is in common with many algorithms designed for maneuvering targets, is of an underlying and hidden "model-switch" sequence, controlled by a Markov probability structure, and controlling the process noise covariance.

**TP09-3**

On alpha-beta target tracking initiation  
Rawicz, Paul L.  
Kalata, Paul  
Chmielewski, T. A.  
Murphy, Kevin  
Drexel Univ.  
Drexel Univ.  
Drexel Univ.  
Drexel Univ.

This paper considers the alpha-beta target tracking initiation process. In particular, we develop an efficient procedure to initialize the target tracker which brings the track from an initial fast rate, through an intermediate rate and into the steady state rate. Alpha-beta parameters for a first order approximation to the Kalman process are developed using a least squares method. The target tracking problem of the Benchmark Challenge is studied for the selection of the intermediate track rate as well as the number of intermediate samples. A comparison of the error covariance is made between the first order linear alpha-beta gain selection and the Kalman processes. It is shown that a performance delay of a few samples results when using a first order alpha-beta gain selection process compared to the Kalman process.

**TP09-4**

Model-set adaptation in variable-structure MM estimation by hypothesis testing  
Li, Xiao Rong  
Univ. of New Orleans

The key component in variable-structure multiple-model (VSM) estimation is model-set adaptation (MSA). This paper formulates MSA as hypothesis testing problems and provides effective solutions, which have some desirable optimally properties. The hypotheses to be tested are in general composite, N-ary, multivariate, and worst of all, not necessarily disjoint. The results form a theoretical foundation and guideline for developing good and practical MSA algorithms.

**TP09-5**

Image based maneuvering target tracking  
Laneuville, D.  
Matra Systemes & Information  
Dufour, Francois  
Bertrand, Pierre P.  
CNRS-ES  
CNRS-ES

This paper presents a new image based target tracking design. The state of the target is described in a hybrid state space where the dynamic of the target is indexed by a discrete variable, the mode or regime, each mode corresponding to maneuver hypothesis. The novelty here is to use the imaging capacity of electro-optical (EO) sensor to improve the tracking performance by better regime estimation than with classical method. This is achieved by a new image based mode estimator that fully exploit the information contained in the pixels. The coupling of this image based mode estimator to an adaptive EKF and to a multiple model tracker akin to the IMM filter is described. The results are illustrated with realistic simulations of an air defense scenario. The efficiency and robustness of this new mode estimator lead to a significant improvement of the tracking performance in both cases.

**TP09-6**

A multiple model framework for image-enhanced tracking of maneuvering targets  
Evans, Jamie  
Evans, Robin J.  
Univ. of Melbourne  
Univ. of Melbourne

We consider tracking algorithms for maneuvering targets when the observations include extra information on the current operating mode of the target obtained from an image sensor. The target is modelled as a Markov jump linear system and the image-based observations form a discrete-time point process. We derive the optimal (minimum mean squared error) filtered estimate which intrinsically fuses the image-based and primary observations. This optimal filter is computationally prohibitive but provides the basis for a clear understanding of various suboptimal approaches. We propose the image-enhanced IMM filter as a practical alternative which retains many desirable properties of the optimal filter and outperforms existing image-enhanced tracking algorithms over a broad range of operating scenarios.

**TP10-1**

A stable scheme for automatic control reconfiguration in the presence of actuator failures  
Boskovic, Jovan D.  
Yu, Ssu-Hsin  
Mehra, Raman K.  
Scientific Systems Co. Inc.  
Scientific Systems Co. Inc.  
Scientific Systems Co. Inc.

The paper describes the design of an automatic control reconfiguration scheme for accommodation of actuator failures in a class of plants where the number of control inputs is larger than the number of controlled outputs. One of the main features of the proposed scheme is that the control reconfiguration is achieved automatically based only on the response of the overall system, and, hence, the controller does not require a Failure Detection and Isolation (FDI) subsystem. The method is developed for a particular type of failures, namely for the case when one or more actuators freeze in a certain position and do not respond to subsequent commands. We assumed that the information about the failure is not available to the controller. This type of failure is particularly severe since the remaining actuators should be reconfigured to not only achieve the control objective, but to also compensate for a disturbance due to the failure. We will show that such a type of failure introduces both constant and state-dependent disturbances into the overall closed-loop system so that the solution to the corresponding control problem is far from trivial. To solve this problem, a control law with adjustable parameters is introduced, and, using a convenient parametrization of the overall system, the resulting error model is expressed in a somewhat modified form as compared to those arising in standard adaptive control. The design of the corresponding adaptive laws based on Lyapunov analysis allow us to prove global stability of the overall scheme in the presence of multiple actuator failures.
This paper deals with the vibration suppression control problem of flexible structures against potential damage. The controller is required not only to robustly stabilize the structure but to satisfactorily suppress the vibration under all predicted damages that might occur in the 20-bay truss structure under study. The damage to the flexible structure we consider here is represented by the various stiffness losses of predetermined elements. The structure with the predicted damages is modeled as an interval transfer function. The controller design is based on the mu-synthesis in conjunction with the extremal properties of interval systems. Unlike conventional mu-synthesis, the technique enables us to use a fixed-size uncertainty block (4 real blocks for SISO case) regardless of the number of parameters, that results in a faster, reliable, and simple synthesis procedure.

TP10-3
Fault detection for time-delay systems by data reconciliation
Kratz, Frederic Roger
LAUT-ENSEM
Nuninger, W.
Inst. National Poly. de Lorraine
Ragot, Jose
Inst. National Poly. de Lorraine

In this note, a method is proposed to detect and localize sensor or actuator failures in time-delay systems. This method is based on analytical redundancy and uses a simultaneous state and input estimation. Basing the method on the concept of standardized least square residuals, residuals can be generated in a number of ways and a corresponding design of fault detection and fault isolation scheme can be presented. Finally, the applicability of the proposed scheme is illustrated on a numerical example.

TP10-4
Model-free fault diagnosis for nonlinear systems: a combined kernel-regression and neural networks approach
Fenu, G.
DEEI-Univ. of Trieste
Parisini, Thomas
DEEI-Univ. of Trieste

In this paper, a novel way of using the Kernel Regression (KR) methodology in the context of model-free fault-detection (FD) for nonlinear systems is proposed. Within the FD context, we propose a completely different way of applying the KR technique. The basic qualitative idea is the following: when a fault occurs, also some change in the smoothness characteristics of the time-behaviors of the measurable variables may occur. This change is reflected in modifications to the typical features of the kernel smoother applied over some suitable temporal batch of the measurable variables, and this could be interpreted as a fault symptom to be fed into the decision scheme based on a neural classifier. The neural classifier may be trained off-line to associate the fault symptoms with some eventual critical behavior of the plant.

TP10-5
A governing equation based fault detection and diagnosis algorithm and its application in a chemical plant
Zhang, Jie
Imperial College
Zhang, Suzhen
East China Univ. of Sci. & Tech.
Thornhill, Nina
Imperial College

This paper describes a governing equation fault detection and diagnosis algorithm, which is extended to deal with multiple faults. The algorithm is specifically designed to overcome disturbances and uncertainties in the process which might result in diagnostic instability. The approach is used to detect and/or diagnose the following faults: sensor faulty status of fails-high and fails-low, sticking valve, plant leaks, and other unanticipated or novel faults. The algorithm was installed on a distributed control system (DCS) of a PET plant in Dec. 1995, and continues to be used thus demonstrating the success of the fault detection and diagnosis approach.

TP10-6
Decentralized fault tolerant stabilization for symmetric composite systems
Huang, Shoudong
Northeastern Univ.
Zhang, Si-Ying
Northeastern Univ.

This paper discusses a class of large-scale systems composed of symmetrically interconnected identical subsystems. The decentralized fault tolerant stabilization problem for such a system is studied. An easily tested necessary and sufficient condition for the decentralized controller of the system to be fault tolerant is presented and a design procedure is given.

TP11-1
Robust decoupled controller design with quantitative feedback theory
Chang, Jin-Chuan
Cheng Cheng Inst. of Tech.
Chang, Yeong-Hwa
Cheng Cheng Inst. of Tech.
Chen, Li-Wei
Cheng Cheng Inst. of Tech.

In this paper, we present a robust decoupled controller design method for MIMO systems by combining Perron-Frobenius theory, Ostrowski's theorem, and quantitative feedback theory. Our aim is to find a required robust controller with less complexity such that the required performances are achieved. An example is given to illustrate the feasibility of the proposed method.

TP11-2
QFT design for uncertain nonminimum phase and unstable plants
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Ballance, Donald J.
Univ. of Glasgow

Design of robust controllers for uncertain nonminimum phase and unstable plants with Quantitative Feedback Theory (QFT) is addressed in this paper. A counterexample for a nonminimum phase plant is given to illustrate the errors in the Horowitz and Sidi method. It is shown that the stability requirement of the new nominal plant is not clearly specified in the existing design method. The stability requirement for the new nominal plant is reformulated and improved design methods for nonminimum phase and/or unstable plants are presented.

TP11-3
An approach to the robust SPR problem through interpolation and avoidance: connections with the robust stability problem
Mosquera, Carlos
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Perez, Fernando
Univ. de Vigo

Convergence of a number of adaptive recursive algorithms, with applications in identification and adaptive control, can be ensured by making a given transfer function strictly positive real (SPR). In some situations a partial knowledge of the system under study is available, thus becoming a robustness problem. In this paper we trace important connections between the classical problem of robust stability and the robust strict positive realness problem, which will allow us to design procedures for solving the robust SPR problem in several different cases.

TP11-4
Design of P, PI and PID controllers for interval plants
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Texas A&M Univ.
Datta, Aniruddha
Texas A&M Univ.
Bhattacharyya, Shankar P.
Texas A&M Univ.

This paper considers the problem of designing P, PI and PID controllers that stabilize an interval plant family. Using results from the area of parametric robust control, these stabilization problems for an interval plant are first reduced to the equivalent problems of stabilizing either certain vertex plants (corresponding to the Khartitonov vertices) or certain segment plants (corresponding to the one-parameter generalized Khartitonov segments). Thereafter, recent results on P, PI and PID stabilization are invoked to obtain a complete characterization of all stabilizing P, PI and PID controllers for an interval plant family.
Robust D-stability via positivity
Siljak, Dragoslav D.
Santa Clara Univ.
Stipanovic, D. M.
Santa Clara Univ.

The main objective of this paper is to convert the general problem of robust D-stability of a complex polynomial to positivity in the real domain of the corresponding magnitude function. In particular, the obtained Hurwitz stability criterion is applied to polynomials with interval parameters and polytopic uncertainty structures. The robust stability is verified by testing positivity of a real polynomial using the Bernstein subdivision algorithm. A new feature in this context is the stopping criterion which is applied whenever the algorithm is inconclusive after a large number of iterations, but we can show that at least one zero of the polynomial is closer to the imaginary axis than a prescribed limit.

TP12-6
Some novel characterizations of generic rank of structured matrix
Li, Kang
Delft Univ. of Tech.
Xi, Yugeng
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Zhang, Yu
National Univ. of Singapore

This paper provides some novel characterizations of the generic rank of structured matrix that is widely used in the study of linear structured systems. Both algebraic and graph-theoretic methods are used to determine the generic rank of structured matrix.

TP12-1
A computational linearization principle for observability of nonlinear DAEs near a trajectory
Terrell, William J.
Virginia Commonwealth Univ.

This paper establishes a result on local observability of nonlinear implicit differential systems near a reference trajectory. Observability of the time-varying linearization along the trajectory implies local observability for the full system in a neighborhood of the trajectory. The conditions for local linearization are verifiable, and provide a link with existing results on observability for implicit systems.

TP12-2
Control design via generalized state space system with state derivative measurement and reciprocal state space system
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Yedavalli, Rama K.
Ohio State Univ.

This paper presents control design methods based on two new frameworks, namely ‘Generalized State Space Systems with State Derivative Measurement’ and the ‘Reciprocal State Space System’. Several performance indices are introduced to allow trade off among different designs which utilize different sensors. The concept of ‘Reciprocal State Space System’ is particularly useful in dealing with the Singular Systems because by using this framework, the design can be accomplished by using existing mathematical tools and software designed for standard state space systems. The design objectives with state derivative feedback can be accomplished much more easily and systematically via the ‘Reciprocal State Space’ framework than with the standard state space framework.

TP12-3
On the reduction of a general 2-d polynomial system matrix to g.s.s. form
McInerney, S. J.
Loughborough Univ.
Pugh, Ashley C.
Loughborough Univ.
Boudellioua, M. S.
Al-Ahsa College of Tech.
Hayton, G. E.
Leeds Metropolitan Univ.

An algorithm which reduces a general 2-D polynomial matrix to an equivalent matrix pencil form is presented and it is shown that, with slight modifications, this algorithm can also be used to reduce a 2-D polynomial system matrix to generalized state space form. The exact nature of the equivalence transformations connecting the different forms are established.

TP12-4
Impulse-free output regulation of singular nonlinear systems
Huang, Jie
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Zhang, Jifeng
Chinese Academy of Sciences

This paper addresses the output regulation problem for the class of singular nonlinear systems. A generalized version of the center manifold theorem that applies to singular nonlinear systems is established first. Then necessary and sufficient conditions are given for the solvability of the output regulation problem. The work extends the existing results of output regulation problem for singular linear systems or normal nonlinear systems to the singular nonlinear systems.

TP12-5
Doubly coprime factorizations for singular system
Gao, Zhiwei
Tianjin Univ.
Wang, Xian-Lai
Tianjin Univ.
Liu, Bao-Kun
Tianjin Univ.
Li, Guangquan
Tianjin Univ.

Firstly, this paper discusses existence and uniqueness of solutions of a class of index-1 singular nonlinear systems. Secondly, this paper discusses stability of zero solution for the singular systems. At last, this paper discusses stability of the singular systems.

TP13-1 (I)
Towards a practical nonlinear predictive control algorithm with guaranteed stability for large-scale systems
Zheng, Alex
Univ. of Massachusetts
Allgower, Frank
Institut fur Automatik ETH, Zurich

In this paper, we propose a Nonlinear Model Predictive Control algorithm that is computationally efficient and guarantees nominal stability for control of large-scale nonlinear constrained systems. The algorithm combines the best features of the algorithms recently proposed by Zheng, and Chen and Allgower.

TP13-2 (I)
Withdrawn

TP13-3 (I)
Nonlinear feedback control of parabolic PDE systems with time-dependent spatial domains
Armaou, Antonio
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Christofides, P.
Univ. of California at Los Angeles

This paper proposes a methodology for the synthesis of nonlinear finite-dimensional time-varying output feedback controllers for systems of quasi-linear parabolic partial differential equations with time-dependent spatial domains. The method is successfully applied to a typical diffusion-reaction process whose spatial domain changes with time and is shown to outperform a controller design method which does not account for the variation of the spatial domain.

TP13-4 (I)
Nonlinearity measures for a class of SISO nonlinear systems
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Univ. of South Carolina
Kosanovich, Karlene A.
Univ. of South Carolina

A new measure of nonlinearity which is defined by two linear systems is proposed to quantify the size of the nonlinearity in the input-output behavior of SISO nonlinear systems. As a result, the task of controller design for the nonlinear system reduces to design a controller for the two linear systems. Two examples are provided to demonstrate these concepts.
Nonlinear model predictive control of a continuous bioreactor at near-optimum conditions

Parker, Robert S.  
Doyle III, Francis J.

Univ. of Delaware  
Univ. of Delaware

The modeling and control of a nonlinear bioreactor system utilizing Volterra-Laguerre models is examined. An analytic solution to the single-input single-output (SISO) unconstrained nominal control problem is described, and a nonlinear model predictive controller (MPC) based on the analytic solution is developed which includes dynamic compensation and manipulated variable weighting. This controller avoids the entrapment in local wells seen in gradient descent nonlinear programming solutions. Additionally, extremum control is performed with no a priori knowledge of the system aside from the identified Volterra-Laguerre representation. In the presence of input magnitude constraints, the analytic controller finds the optimal input move in the feasible region. Initial extensions to the mismatch case are also examined.

TP13-6 (I)  
Wastewater neutralization control using a neural network based model predictive controller

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Melsheimer, Stephen S.

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Clemson Univ.

Neutralization is an important and common technique used in the wastewater treatment. The purpose of neutralization is to adjust the pH value to meet the requirements of the different processing units in the wastewater treatment system. Although the importance of this technique and extensive study has been devoted to neutralization control, there are still a lot of control problems in the industrial wastewater neutralization because of the nonlinearity of the titration curve, variable buffering, changes in loading. In order to cope these problems, many authors propose different solutions such as modified PI controller, adaptive control and predictive adaptive control. One of the alternative control schemes recently applied to the pH control of chemical process is the use of Model Predictive Control (MPC). A Neural Network based Model Predictive Controller (NNMPC) is developed in this paper. In order to study the effectiveness of NNMPC, a simulation case of wastewater neutralization process was chosen as a test case.

TP14-4 (I)  
Experiments in robust control on a laboratory model of a six story building

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Craig, J. I.  
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Georgia Inst. of Tech.  
Georgia Inst. of Tech.

This reports a series of experiments performed to quantify the potential benefits of using robust control design methodology in active control of building structures. The experimental facility is described, and the design approaches which include H2 design, Mussythesis and mixed H2/Mu design are outlined. Experimental results show the ability of the robust control systems to tolerate uncertainty due to high frequency unmodeled modes and due to uncertainty in the natural frequency of the modeled modes.

TP14-6 (I)  
Integrated design of controlled engineering systems

Skelton, Robert E.

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This paper presents a MATLAB tool for interactive transfer function analysis which can be used to enhance students and engineers understanding of system characteristics and behaviour. It allows a user to develop an intuitive feeling for the relationship between time and frequency domains, and locations of roots of a transfer function. The MATLAB software tool described in this paper allows for interactively designing a system described by a linear transfer function. During the design process in either the Laplace domain, the frequency domain or the time domain, the system characteristics will be simulated on-line in the other domains.
Many classes of feedback control designs can be reformulated as a static output feedback optimization problem. Previous work by Burchett and Costello has exploited direct ways to compute the H2 optimal output feedback gains using dyadic decomposition and analytic derivatives of the eigensystem. This work presents a modification of this technique with application to H-infinity performance optimization. Analytic derivatives of the Singular Value Decomposition (SVD) are central to this method. The method is applied to two aircraft flight control problems.

TP15-3  Nonlinear aircraft control using a minimal radial basis function neural network
Nigel, Chua Boon Hong Nanyang Tech. Univ.
Sundararajan, N. Nanyang Tech. Univ.
Saratchandran, P. Nanyang Tech. Univ.

In this paper, a nonlinear inverse flight controller for fighter aircraft is designed using the recently developed Minimal Resource Allocation Neural Network (MRAN) learning algorithm. MRAN has been shown to produce a minimal radial basis function network. The performance of the MRAN controller for the F-22 aircraft is highlighted for following pilot commands.

TP15-4  Stochastic modeling of fatigue crack dynamics for risk analysis and remaining life prediction
Ray, Asok Pennsylvania State Univ.

This paper presents a stochastic dynamic model of fatigue crack propagation in metallic materials which are commonly encountered in mechanical structures and machine components of complex systems (e.g., aircraft, spacecraft, and power plants). The (non-stationary) statistics of the crack growth process are obtained without solving stochastic differential equations in the Wiener integral or integral MRAN setting. The crack propagation model thus allows real-time execution of decision algorithms for risk assessment and life prediction on inexpensive platforms such as a Pentium processor. The model predictions are in close agreement with experimental data of fatigue crack statistics for 2024-T3 and 7075-T6 aluminum alloys.

TP15-5  Cumulants-based ANFIS modeling
Zhou, S. C. Hong Kong Polytechnic Univ.
Wong, T. T. Hong Kong Polytechnic Univ.
Leung, T. P. Hong Kong Polytechnic Univ.
Shuai, O. L. South China Univ. of Tech.

This paper introduces a new lower bound stability measure with Finite-Word-Length (FWL) considerations that provides a larger measure than existing bounds and gives a better estimation of the stability robustness of sampled data system with FWL controller implementations. The optimal realization problem of the digital PID controller with FWL considerations is addressed. This parameterization problem is formulated as a nonlinear programming problem with a maximum of four independent variables. A strategy based on Rosenbrock's hill climbing algorithm to solve the optimal realization problem of digital PID realizations is developed, and the methodology is applied to a steel rolling mill to illustrate the effectiveness of the new measure.

TP16-2 (I)  Active control of a reverberant enclosure using an approximate constant volume velocity source
Lane, Steven A. Duke Univ.
Clark, Robert L. Duke Univ.

Transduction device dynamics are an important consideration in active feedback control of acoustic enclosures. This work considers a feedback control strategy to dissipate acoustic energy in a reverberant enclosure based on using a single, closely collocated microphone and loudspeaker, in conjunction with constant gain feedback. The loudspeaker is compensated so that it approximates a constant volume velocity source over the piston mode frequency range. This effectively removes the transduction device dynamics from the bandwidth of control and yields a controller that more efficiently removes acoustic energy from the system over the piston mode frequency range. The control approach is used to attenuate low frequency broadband noise in a rigid wall enclosure. In addition, a dynamic, state-space, H2 controller is implemented on the system for comparison. The results indicate that the proposed controller performs nearly as well as the model-based, dynamic controller for the same control energy.

TP16-3 (I)  Active acoustic treatment (AAT) - a step toward a perfect sound absorber
Mehta, Prashant G. United Technologies Research Ctr.
Zander, Anthony United Technologies Research Ctr.
Patrick, Bill United Technologies Research Ctr.
Zhang, Youping United Technologies Research Ctr.

Active Acoustic Treatment (AAT) is proposed as a method to absorb noise propagating in a duct with the objective of reducing the total noise power radiated from the duct exit. The effectiveness of AAT concept in attenuating both planar and higher-order acoustic duct modes is investigated experimentally in a rectangular duct. Decentralized feedback control is proposed as the control solution and is shown to perform satisfactory. The performance of AAT is measured using 1) acoustic mode decomposition with microphone arrays located in the duct, upstream and downstream of the AAT sheet, and 2) a single microphone located external to the duct exit. Experimental results are included to demonstrate the attenuation of the total acoustic power propagating in the duct, and the reduction of the noise radiated from the duct.

TP16-4 (I)  Active noise control for periodic disturbances
Bodson, Marc. Univ. of Utah
Jensen, Jonathan S. Univ. of Utah
Douglas, Scott C. Univ. of Utah

This paper proposes an active noise control algorithm for periodic disturbances of unknown frequency. The algorithm is appropriate for the feedback case in which a single error microphone is used. A previously-proposed algorithm for the rejection of sinusoidal noise sources is extended for the cancellation of multiple harmonics. Unlike many other approaches, the estimates of the frequencies of the separate harmonics are tied together within the algorithm to account for the integer multiplicative relations between them. The dynamic behavior of the closed-loop system is analyzed using an approximation that is shown, in simulations, to provide an accurate representation of the system's behavior. Experimental results on an
active noise control testbed demonstrate the success of the method in a practical environment.

TP16-5 (I)
Designing ANC systems directly from frequency responses
Hollot, Christopher V. Univ. of Massachusetts
Chait, Yossi Univ. of Massachusetts

In this presentation, we will report on a technique to design feedforward compensators for broadband attenuation in ducts. This technique does not require open-loop system identification and uses loop-shaping techniques to design compensators directly from frequency response measurements. The potential benefits of this technique include: reduced design cycle-time, lower-order compensators and improved insight into design tradeoffs.

TP16-6 (I) 2621
Active control of noise using a pneumatic servovalve
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Bernstein, Dennis S. Univ. of Michigan

In this paper we demonstrate the applicability of a high speed pneumatic servovalve for active noise control (ANC). Pressurized air is fluctuated using the servovalve to produce sound at commandable amplitude and frequency. The paper presents results of a noise cancellation experiment with a acoustic duct structure where disturbance produced by a speaker is overwhelmed by the high speed pneumatic servovalve. Single-tone and dual-tone disturbances at unknown frequencies are successfully rejected using the ARMAKOV adaptive control disturbance rejection algorithm.